THE JOURNAL of the Acoustical Society of America

• CONTENTS •

Observations on the Vibrations of Piano Strings . . . . O. H. Schuck and R. W. Young 1

Mean-Tone Temperament. The Classical System of Instrumental Tuning . . . . . William Braid White 12

Supersonic Measurements in CO_2 and H_2O at 98° C . W. H. Pielemeier and W. H. Byers 17

Supersonic Measurements in CO_2 at 0° to 100° C . . . . . W. H. Pielemeier 22

Application of Sound Absorption to Factory Noise Problems . . . . . Hale J. Sabine and R. Allen Wilson 27

Improved Telephone Receiver Analysis . . . . . R. D. Fay 32

Damping of Large Amplitude Vibrations of a Fluid in a Pipe . . . . . R. C. Binder 41

Conditions for Wide Angle Radiation from Conical Sound Radiators . Richard W. Carlisle 44

Mechanical Impedance Bridge . . . . . A. M. Wiggins 50

Direct Observations of the Acoustic Oscillations of the Human Ear . . . . H. G. Kobrak 54

Is the Threshold Audiogram Sufficient for Determining Hearing Capacity? . . . . . Edmund Prince Fowler 57

Scientific Research and Political Regulation 61

Current Publications on Acoustics

- Acoustical Society News 62
- Book Review 64
- References to Contemporary Papers on Acoustics 65
- Review of Acoustical Patents . . . . . Robert W. Young 67

Program of the Twenty-Eighth Meeting of the Acoustical Society of America, Hotel Pennsylvania, New York, New York, May 14–15, 1943: Abstracts 1-28: Author Index . . . 81

Vol. 15, No. 1 JULY, 1943

THE JOURNAL
OF THE
ACOUSTICAL SOCIETY OF AMERICA

Volume 15 Number 1

JULY • 1943

Observations on the Vibrations of Piano Strings *

O. H. SCHUCK AND R. W. YOUNG
C. G. Conn, Ltd., Elkhart, Indiana

(Received May 24, 1943)

The behavior of single piano strings struck in their normal positions was investigated through measurement of the frequencies of the partials and their amplitudes as functions of time after striking. Three-dimensional figures showing partial amplitudes *versus* time are presented. The frequencies of the partials of the tone were found to be those of the normal modes of vibration and are therefore referred to as the modal frequencies of the string. The higher modal frequencies are progressively sharp with respect to true harmonics of the fundamental; the sharpening follows approximately a square law with respect to mode number, to the extent that in one case the 15th partial had just about the frequency of a 16th harmonic. The resulting inharmonicity in piano strings is least in the two octaves below middle *C*; it rises sharply at the high end and more or less sharply at the low end, depending upon the type of piano. A correlation between inharmonicity and subjective tone quality rating is suggested. It is shown that the commonly observed "stretched" tuning (sharpening of the treble, flattening the bass) is a natural consequence of the inharmonicity.

INTRODUCTION

INVESTIGATION of the tone and vibration of the piano string, when strung in the piano and struck by the hammer in normal fashion, is complicated by the transitory nature of the phenomenon. However, it is possible to make such studies by separating out one partial of the tone at a time with a selective filter. This partial's amplitude variation with time after striking may then be recorded with a high-speed graphic level recorder and its frequency may be determined with a chromatic stroboscope. These data, taken for each of the distinguishable partials in the tone, indicate the nature of the tone quality and furnish information regarding the vibration of the string. Some observations of this kind are described below, and their significance is discussed, both in relation to tone quality and the tuning of pianos.

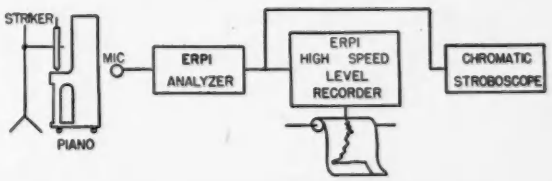
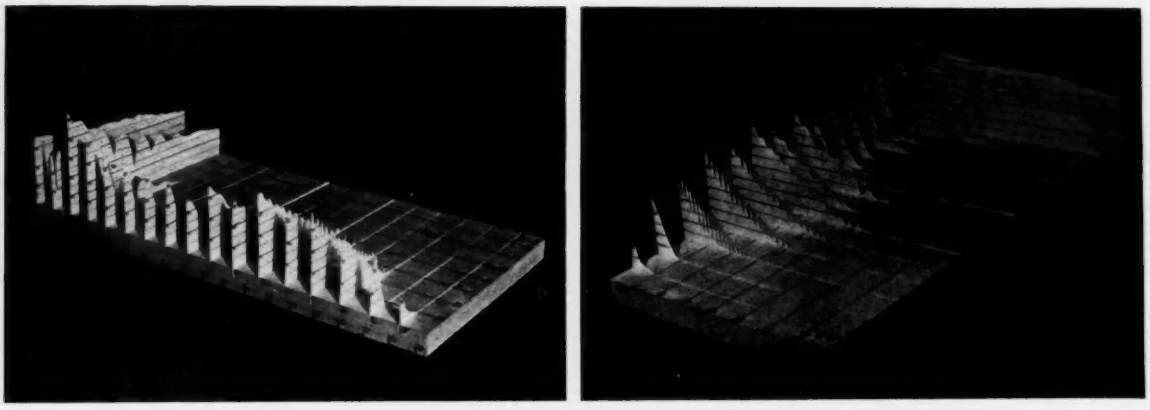


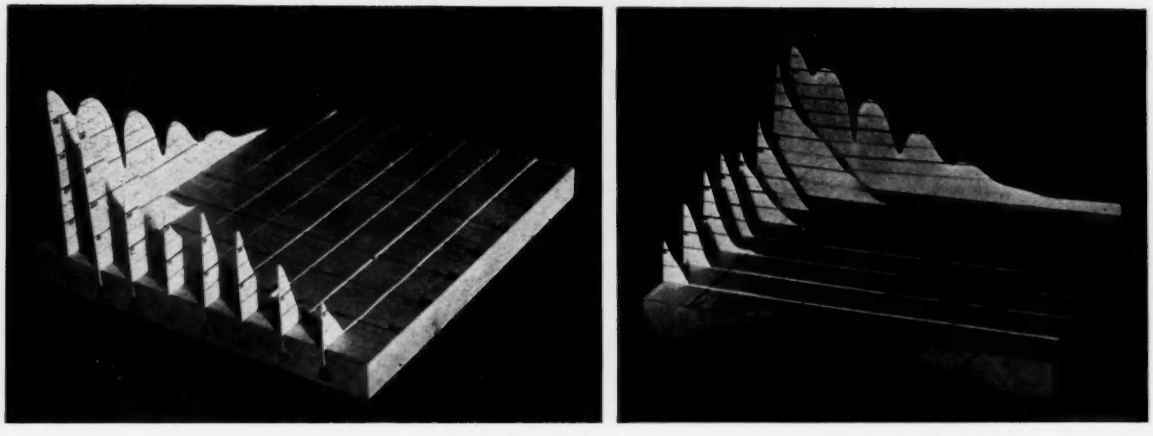
FIG. 1. Apparatus for measuring amplitudes of partials.

* Paper presented at the twenty-eighth meeting of the Acoustical Society of America, May 14–15, 1943, New York, New York.



(a) (b)

FIG. 2. Amplitudes of the partials of an F_1 string as functions of time.



(a) (b)

FIG. 3. Amplitudes of the partials of an F_3 string as functions of time.

AMPLITUDE OF PARTIALS *VERSUS* TIME

Figure 1 shows the arrangement of apparatus for measuring the variation of amplitude with time after striking, for each partial of a piano tone. The selected key is struck by a mechanical striker; when the key has two or three strings, only one is left free to vibrate. The sound is picked up by a microphone, fed through an analyzer which is tuned to one partial; the amplitude of this partial is recorded by the high speed level recorder, while its frequency is read on the chromatic stroboscope. A record is run for each of the ascending partials until they can no longer be distinguished. The records are similar in form to the examples obtained by Wolf and Sette.[1]

[1] S. K. Wolf and W. J. Sette, J. Acous. Soc. Am. **6**, 160–168 (1935).

In order to present the results in a form readily comprehended, fiber templets were cut from the level recorder records and mounted on slotted boards to form three-dimensional figures, as shown in Figs. 2 and 3. Figure 2 represents the tone from the F_1 string—the lowest F—on a small console piano. Similarly, Fig. 3 represents the tone from one string of the key F_3—the third F, the F below middle C—on the same piano. The ordinates are on a logarithmic scale.

It is seen that after the initial peak at striking,

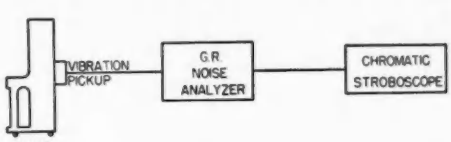


FIG. 4. Method for determining modal frequencies of piano strings.

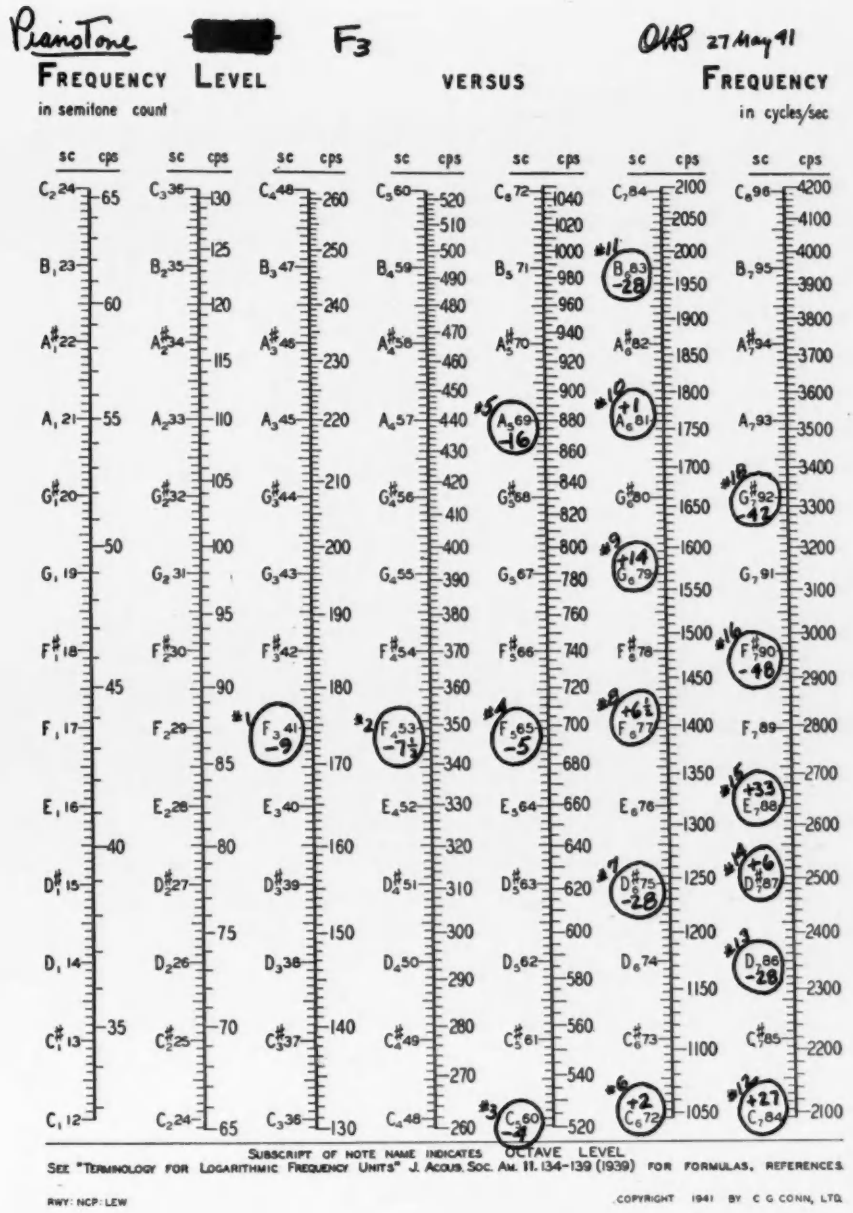

PianoTone [redacted] F3
OHS 27 May 41
FREQUENCY LEVEL VERSUS FREQUENCY
in semitone count
in cycles/sec
sc cps
SUBSCRIPT OF NOTE NAME INDICATES OCTAVE LEVEL
SEE "TERMINOLOGY FOR LOGARITHMIC FREQUENCY UNITS" J. ACOUS. SOC. AM. 11. 134-139 (1939) FOR FORMULAS, REFERENCES
RWY: NCP: LEW
COPYRIGHT 1941 BY C G CONN, LTD.

FIG. 5. Frequency level conversion chart used as a data sheet.

which is more rapid in its rise than the high speed level recorder can follow (the nominal maximum being 50 db/sec.), there is a fairly uniform rate of decrease in amplitude, the rate of decrease being more rapid the higher the number of the partial. This is to be expected from the increased air loading of the string and sounding board at the higher frequencies. The tone quality therefore changes continuously, becoming less complex as time goes on.[2] Particularly in the tone produced by the longer string (Fig. 2) the amplitudes of the partials show large fluctuations of a form suggesting half sine waves. The higher the partial, the more rapid the fluctuations. This condition may be due to rotation of the plane of vibration of the string, and there

[2] Hart, Fuller, and Lusby, J. Acous. Soc. Am. **6**, 92 (1934).

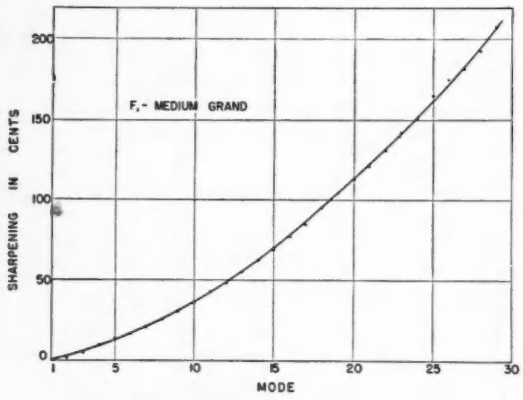


FIG. 6. Inharmonicity for the F_1 string of a medium grand piano.

may also be some transfer of energy from one mode to another. It is interesting to notice that the seventh partial is not particularly weak, despite the fact that the striking point is often stated to be at one-seventh of the string length to suppress this partial.

The frequency scale used in making the three-dimensional figures is linear: Harmonics would therefore appear equally spaced. The templates have been located to correspond to the measured frequencies. As is particularly evident in Fig. 2a, the frequencies of the partials are not harmonic. Along the edge of the board the number of the mode of vibration which produces each partial is indicated in the upper row of figures; in the lower row the position of each true harmonic is shown. It is seen that the partials are progressively sharpened, indeed to the extent that the 15th partial has just about the frequency of a 16th harmonic. True harmonics of the fundamental frequency could not be found. This fact indicates that the transmission system from string to air is relatively distortionless, and that the partials in the tone are indeed produced by the respective modes of vibration of the string.

It should be pointed out that these amplitude data are unquestionably influenced by the room conditions, and are only to be considered as indicating the practicability of making measurements of this kind. On the other hand, the frequencies of the partials are not influenced by the room conditions. Their measurement is relatively simple and since their influence on tone quality was considered important, all of the further work described here was concerned only with such frequency measurements.

FREQUENCIES OF PARTIALS

The frequencies of the various partials of a struck piano string were measured by the apparatus shown in Fig. 4. (Since these frequencies are those of the normal modes of vibration they are hereafter referred to as the modal frequencies.) The output of a crystal vibration pick-up fastened to a rib of the sounding board was fed through an analyzer to a chromatic stroboscope. Only one string of the group being struck was left free to vibrate. As it was found that variations in the strength of the blow produced negligible effects on the modal frequencies, the key was struck manually.

Rapid recording of the data was facilitated by use of the frequency level *versus* frequency chart shown in Fig. 5, this being the actual work sheet of one run. The number of cents

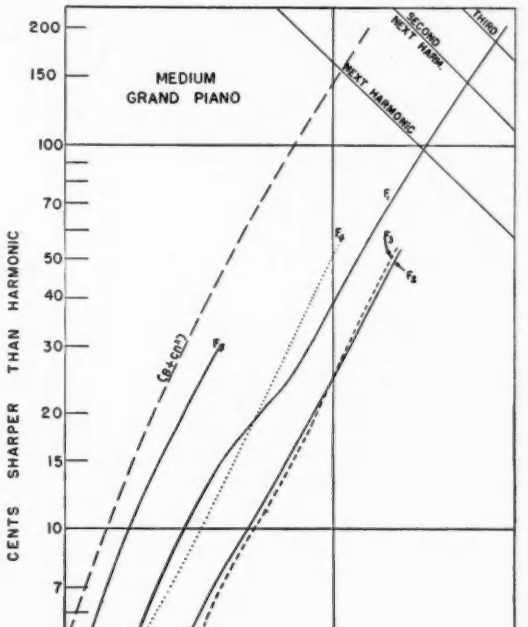


FIG. 7. Inharmonicity as some power of mode number.

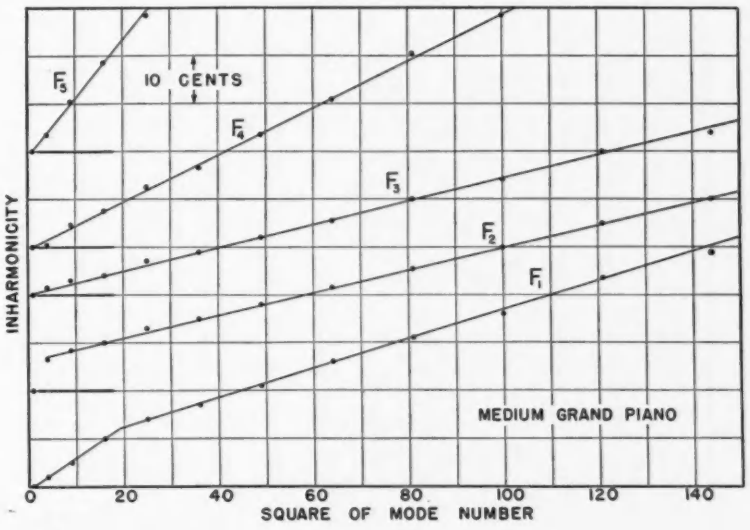


FIG. 8. Inharmonicity as a function of the square of mode number.

deviation measured with respect to a nominal value is encircled; the corresponding mode number is indicated alongside.

The readings are in terms of frequency level,[3,4] so the percentage sharpening of each partial with respect to a true harmonic is easily obtained by a subtraction procedure which is described in the Appendix. We call this percentage departure from harmonicity the "inharmonicity." More specifically it is convenient to measure and express the inharmonicity as the number of *cents* by which a particular modal frequency ν departs from its nominal value $n\nu_1$, where ν_1 is the fundamental frequency and n is the mode number. This departure, the inharmonicity D, is therefore

$$D=1200\log_2(\nu/n\nu_1). \tag{1}$$

It may be recalled that the cent is one hundredth of a semitone, so there are 1200 to the octave; one cent corresponds to a percentage difference in frequency of 0.06 percent. D is zero if the modal frequency is exactly harmonic.

The inharmonicities of the modal frequencies of one string in a medium grand piano are shown in Fig. 6, plotted against the number of the mode. Note that the inharmonicity follows a fairly smooth curve and is always positive. This means that the partials are always sharp with respect to true harmonics. When the inharmonicity *versus* mode number is plotted on log-log paper, as shown in Fig. 7, the observed points for a number of strings measured in the medium grand piano fall, respectively, on fairly straight lines whose slopes are close to 2. This means that approximately

$$D=1200\log_2\nu/n\nu_1\backsimeq Kn^2, \tag{2}$$

where K is some factor of proportionality. This is nearly equivalent to

$$\nu=n\nu_1[1+(K/1731)n^2], \tag{3}$$

as may be shown by substitution back in Eq. (2) and using the appropriate expansion for the logarithm.

This proportionality to n^2 is of the form predicted by theory for stiff strings and various boundary conditions,[5-7] provided that the terms independent of mode number are absorbed in ν_1.

The line in Fig. 7 labeled "next harmonic" indicates at what point a particular mode has been sharpened to the extent that its frequency is equal to that of a true harmonic one number greater. Similarly, the intersection of the curve for F_1 near $n=23$ with the line "second next

[3] H. Fletcher, J. Acous. Soc. Am. **6**, 59–69 (1934).
[4] R. W. Young, J. Acous. Soc. Am. **11**, 134–139 (1939).
[5] Lord Rayleigh, *Theory of Sound* (Macmillan, 1894), second edition, Vol. I, p. 301.
[6] R. S. Shankland and J. W. Coltman, J. Acous. Soc. Am. **10**, 161–166 (1939).
[7] P. M. Morse, *Vibration and Sound* (McGraw-Hill, 1936), p. 131.

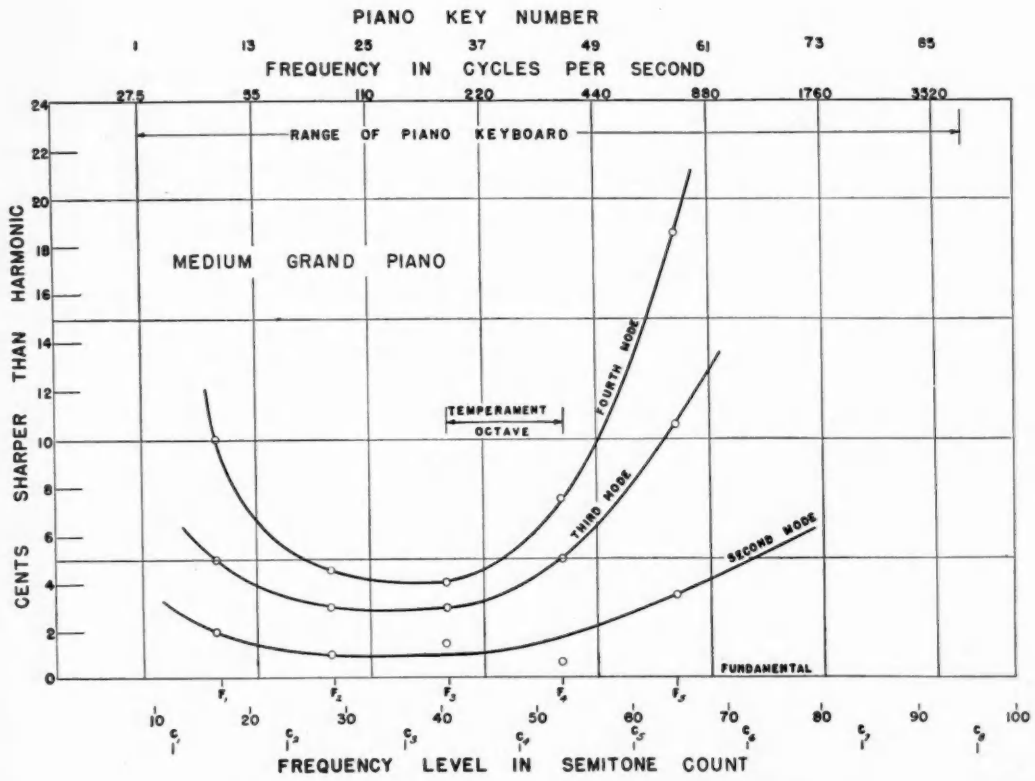


FIG. 9. Inharmonicity in relation to position of string in piano.

harmonic" means that the frequency of this mode of vibration is approximately 25 times that of the fundamental.

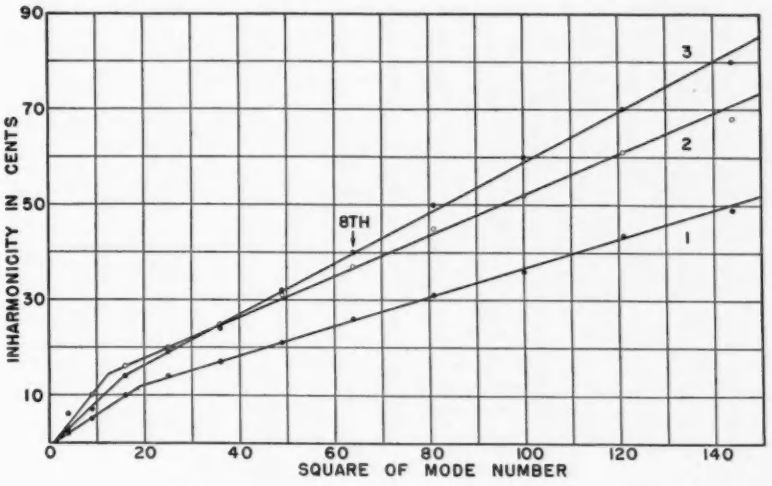
In order to investigate the "square" relationship in detail the inharmonicity *versus* square of mode number has been plotted in Fig. 8, again using the data on the medium grand piano. The curves have been given an arbitrary vertical displacement for clarity. The straight lines are for convenience in visualizing the relationship; actually only discrete values of the inharmonicity exist corresponding to the mode numbers.

For the higher pitched strings a single straight line constitutes an excellent fit. For the lower ones a constant should be added to the second member of Eq. (2), and the exponent reduced to something less than 2. The effect of such an additive constant is illustrated by the curvature of the dashed line in Fig. 7 labeled $(B+Cn^2)$, where B and C have been chosen arbitrarily. Such a complication should perhaps be expected for F_1, in consideration of yielding of the end supports and the heavy loading.

COMPARISON OF STRINGS

From Figs. 7 and 8 it is apparent that the inharmonicity is not the same for all strings. In Fig. 9 the inharmonicity for several of the lower modes is replotted against frequency level and position on the piano keyboard. The sharpening is least in the two octaves below middle C and increases rapidly below and above this region. In fact, it shows signs of reaching quite surprising values at the top end of the keyboard. This is quite plausible for the top strings are so short and stiff as to be really more like bars than strings.

One would surmise that, since all pianos have about the same string dimensions in the middle and upper registers, there would be little variation here in the inharmonicity among different pianos. On the other hand, the lengths of the bass strings vary with the size of the piano, and one would accordingly expect variations in the inharmonicity in the low register. These expectations were corroborated by measurements on different sizes of pianos.



	8th Mode	Slope
1. Medium Grand	26	0.31
2. 39″ Console	37	0.42
3. 36″ Console	40	0.53

FIG. 10. Comparison of the inharmonicity of F_1 for various pianos.

Figure 10 gives a comparison of the inharmonicity of the F_1 strings of several pianos, again plotted against the square of the mode number for convenience. The inharmonicity is less for the larger piano. The eighth modes, for example, were respectively 26, 37, and 40 cents sharper than the corresponding harmonic values. This observation is in line with the widely held opinion that the piano with longer bass strings has a "rounder, fuller, richer tone." Let us consider this point philosophically for a moment.

It is generally agreed that a tone is round, full, and rich if it consists of a fundamental and a long series of harmonic overtones of gradually decreasing amplitudes. Nevertheless, if the fundamental is missing or weak, as it often is in the lower tones of a piano, the listener will still imagine he hears a fundamental in the series and be pleased with the tone. This subjective fundamental is derived from the differences between the successive partials. When they are harmonically related as when produced, for example, by a horn, the frequency differences between successive partials are constant, and the derived fundamentals all have the same frequency, which is that of the actual fundamental. However, if the partials are not harmonically related, as in the piano tone, the various derived fundamentals do not have the same frequency, there is confusion in the ear, and the tone is not considered pleasing.

The inharmonicity of some arbitrarily selected mode therefore constitutes a simple criterion of excellence of a string. However, particularly for bass strings, the fundamental is often almost lacking, so the accurate determination of the interval from the fundamental to the eighth mode, say, is not always easy. Moreover, the manner in which the inharmonicity changes with mode number may vary among different pianos. On the hypothesis suggested above it is the differences between successive partials which are significant, so that the rate of increase of inharmonicity with mode number is pertinent. The caption with Fig. 10 shows also this method of rating, the slope relative to n^2 having been used for simplicity. Observe that although pianos 2 and 3 had nearly the same inharmonicity of the eighth mode, the greater slope of the curve 3 indicates a greater spread of differences between successive partials. This criterion of slope relative to n^2 may be determined experimentally with accuracy in a straightforward manner. On the other hand, there may be needed some power of mode number other than two, and the criterion does not recognize that the subjective fundamental created within the ear will depend upon the actual frequencies and

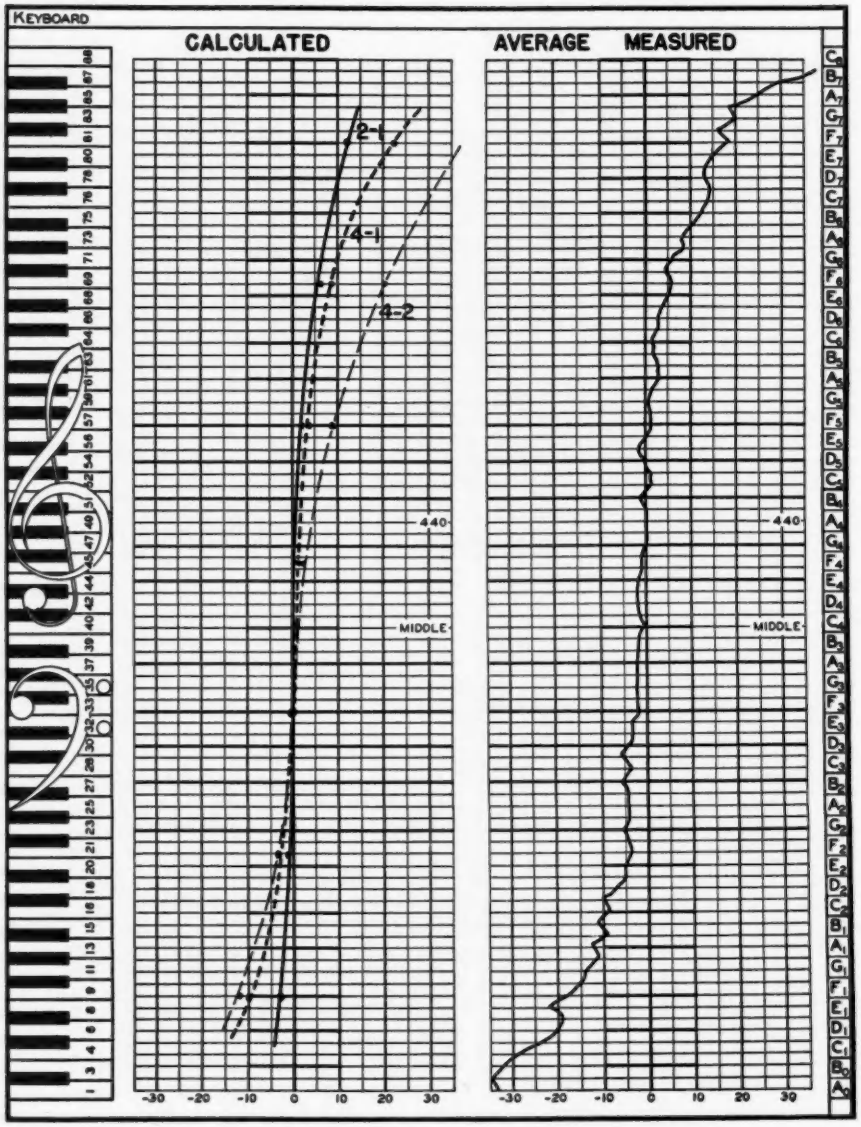


FIG. 11. (a) Left: Calculated tunings, showing deviations in cents.
(b) Right: Average of 16 pianos tested by Railsback.

relative amplitudes of the various partials involved.

That the longer string is desirable for its better tone quality is appreciated by the piano designer,[8] who takes considerable pains to make the bass strings as long as the dimensions of the case will allow.

EFFECT OF INHARMONICITY ON TUNING

There is another effect of interest produced by the inharmonicity of the partials. Measurements by Railsback[9] show that piano tuners usually tune progressively sharp in the middle and high registers, progressively flat in the low. The process of piano tuning[10,11] is carried out by "laying the temperament" in an octave in the middle of the keyboard—usually the octave from F_3 to F_4—and then tuning up and down by octaves. To tune upward by an octave, one

[8] W. B. White, J. Acous. Soc. Am. **12**, 409–411 (1941).

[9] O. L. Railsback, J. Acous. Soc. Am. **9**, 274 (1938); **10**, 86 (1938).

[10] G. F. H. Harker, J. Acous. Soc. Am. **8**, 243–256 (1937).

[11] W. B. White, J. Acous. Soc. Am. **9**, 47–50 (1938).

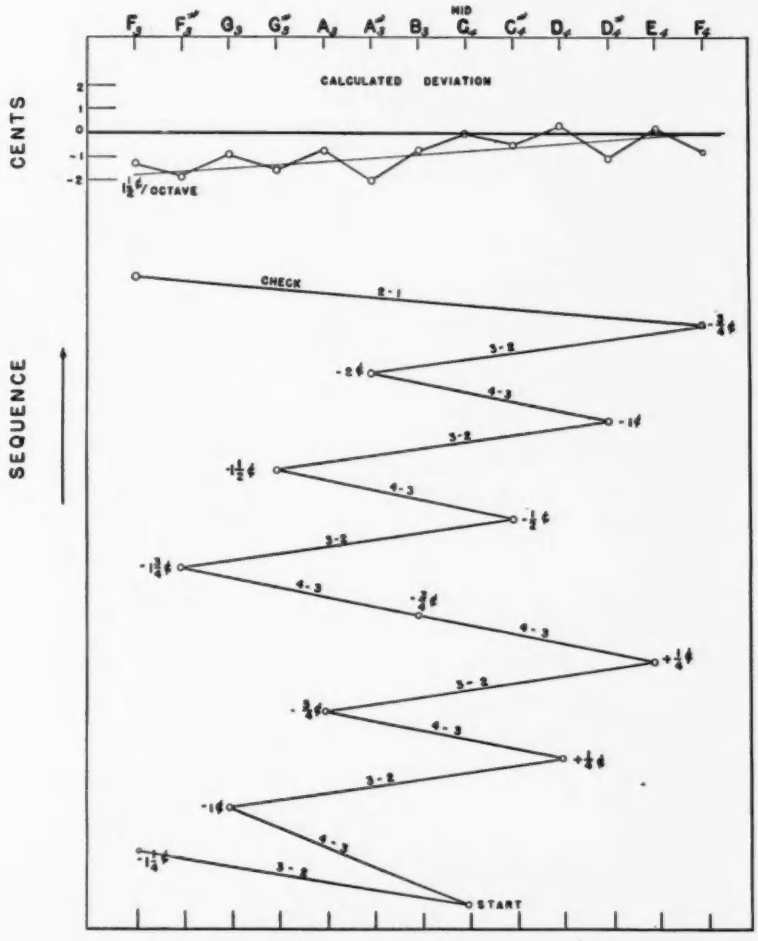


FIG. 12. Deviations from equal temperament within an octave resulting from inharmonicity.

adjusts the tension of the upper string until its fundamental has the same frequency as the second mode of the lower string, as indicated by the absence of beats. If the second mode of the lower string is sharper than a true second harmonic of the fundamental, then the upper string's fundamental will be tuned sharp. The next octave jump will increase the sharpening still further, particularly since the inharmonicity increases toward the high end, as shown in Fig. 9. From the curve there given for the second mode one can derive the expected tuning curve for this particular piano as given by (2–1) in Fig. 11, in which deviations from nominal equal temperament are given in cents. It is seen to be very similar in shape to the average tuning curve found by Railsback (right-hand curve), although its deviations are not as great as he shows.

If the fundamental is missing or weak, as is often the case in the lower register, it may be that rather than beating first and second, the tuner is actually adjusting the second partial of the upper tone to have the same frequency as the fourth partial of the lower tone. When this is the case the tuning curve marked (4–2) in Fig. 11 should be obtained. It has the same shape as (2–1), but its deviations are much greater, even greater than those of Railsback's average curve in the upper register. However, it is quite comparable in the lower register where this method of tuning is more likely to be used.

A tuner often checks his tuning by double octaves, that is, beating the fourth partial of the lower tone against the fundamental of the upper tone. If this were done as a tuning procedure, the resulting tuning curve would be that labeled

(4–1) in Fig. 11, which is seen to fall between the curves. Which of these methods of tuning is actually used, and in which section of the keyboard, appears to depend upon the individual tuner and the particular piano he is tuning.

In laying the temperament initially the tuning is also affected somewhat by the sharpening of the partials. The tuner adjusts the fundamental of one string to his tuning fork, then adjusts another string to the first by listening for beats between partials of the same approximate frequency. He adjusts the beats to be in accordance with a table calculated on the assumption that the partials are truly harmonic. In Fig. 12 is illustrated the sequence used by one tuner. Starting at the bottom with C_4 (middle C), the lines indicate the intervals being adjusted, each being labeled with the partials which are beating. Taking the corresponding inharmonicities from Fig. 9 and subtracting gives the amounts in cents by which the intervals are long. The resulting tuning is plotted at the top of the figure and is seen to be somewhat irregular, but the general rise is quite similar to that often found throughout the middle register of the piano.

TABLE I. Semitones corresponding to numbers to 50. Semitones $= \log_{2^{1/12}} N = 12 \times \log_2 N$. 100 cents = 1 semitone.

N	Semitones Interval	Cents	N	Semitones Interval	Cents
1	0.00	0.00	26	56.41	5640.53
	12.00			0.65	
2	12.00	1200.00	27	57.06	5705.87
	7.02			.63	
3	19.02	1901.95	28	57.69	5768.82
	4.98			.61	
4	24.00	2400.00	29	58.30	5829.58
	3.86			.59	
5	27.86	2786.31	30	58.88	5888.27
	3.16			.57	
6	31.02	3101.95	31	59.45	5945.04
	2.67			.55	
7	33.69	3368.82	32	60.00	6000.00
	2.31			.53	
8	36.00	3600.00	33	60.53	6053.27
	2.04			.52	
9	38.04	3803.91	34	61.05	6104.95
	1.82			.50	
10	39.86	3986.31	35	61.55	6155.14
	1.65			.49	
11	41.51	4151.32	36	62.04	6203.91
	1.51			.47	
12	43.02	4301.95	37	62.51	6251.34
	1.39			.46	
13	44.41	4440.53	38	62.98	6297.51
	1.28			.45	
14	45.69	4568.82	39	63.42	6342.48
	1.19			.44	
15	46.88	4688.27	40	63.86	6386.31
	1.12			.43	
16	48.00	4800.00	41	64.29	6429.06
	1.05			.42	
17	49.05	4904.95	42	64.71	6470.78
	0.99			.41	
18	50.04	5003.91	43	65.12	6511.51
	0.94			.40	
19	50.98	5097.51	44	65.51	6551.32
	0.89			.39	
20	51.86	5186.31	45	65.90	6590.22
	0.84			.38	
21	52.71	5270.78	46	66.28	6628.27
	0.81			.37	
22	53.51	5351.32	47	66.66	6665.51
	0.77			.36	
23	54.28	5428.27	48	67.02	6701.95
	0.74			.36	
24	55.02	5501.95	49	67.38	6737.65
	0.71			.35	
25	55.73	5572.63	50	67.73	6772.63
	0.68				

TABLE II.

1 n	2 sc	3 sem	4 sc	5 cents
1	40.91	0.00	40.91	
2	52.92	12.00	40.92	1
3	59.96	19.02	40.94	3
4	64.95	24.00	40.95	4
5	68.84	27.86	40.98	7
6	72.02	31.02	41.00	9
7	74.72	33.69	41.03	12
8	77.06	36.00	41.06	15

Column headings: 1. Mode number; 2. Frequency level; 3. Nominal harmonic interval; 4. Frequency level of "reduced" fundamental; 5. Inharmonicity.

The measurements described here indicate that the "stretched"[11] tuning is a natural result of the inharmonicity of the partials of the piano tone and is perhaps necessary if the piano is to sound in tune with itself. Whether or not stretching is desirable may therefore depend upon the size and construction of the piano and whether it is to be used alone or with other instruments.

CONCLUSION

The observations described above, while admittedly preliminary, show definitely that the actual strings used in the piano do not behave like idealized strings. Their modal frequencies do not follow exactly the harmonic series, but are progressively sharp with respect to true harmonics. At least within certain limits the inharmonicity is approximately proportional to the square of the mode number, and increases considerably toward the upper and lower ends of the keyboard. It seems to be about the same

in the middle and upper registers of different pianos, but to be less in the lower registers of pianos with longer bass strings. These observations lead to a plausible explanation of the better tone quality generally ascribed to pianos with longer bass strings.

A consideration of piano tuning procedure indicates that the effect of the inharmonicity is to produce just the sort of deviations in tuning that have actually been observed. Much work remains to be done to add to the data here presented, to study in detail the effects of bridge forms, braces, and string construction, and to investigate further the influence on tuning.

The authors are indebted to O. M. Salati and O. H. Kraushaar for their cooperation in making the measurements.

APPENDIX

Routine for Establishing Inharmonicity

The basis of this method is the comparison of the logarithms of the ratios of the modal frequencies with the logarithms of the nominal ratios. Furthermore, by choosing as the base of logarithms $2^{1/12}$, the ratios are measured directly in semitones (or cents), and are thus capable of convenient interpretation in terms of the musical intervals.

Table I gives these logarithms for integers to 50. This represents an expansion of a similar table published by Wead[12] and a few corrections have been made. The table shows, for example, that a true seventh harmonic is 33.69 semitones above the fundamental, and that the interval between the seventh and eighth harmonics is 2.31 semitones.

Table II illustrates the subtraction process, based on the data given in Fig. 5. The eighth mode, for example, was found to have a frequency level of 77.06 sc (semitones counted from a reference frequency of 16.35 cycles/sec.). Upon subtracting 36.00 from this value we obtain the frequency level of the fundamental, had this mode been harmonic. Then by subtracting the frequency level of the measured fundamental we arrive at the number of semitones (rather with the decimal point moved over for cents) by which each mode exceeds its harmonic value. The last step is unnecessary in constructing curves as in Fig. 10, since the frequency level of the "reduced fundamentals" may be plotted directly. This is a convenience when an accurate measurement of the fundamental frequency is not available.

The position at which to match the nominal intervals is found by inspection. If the differences in column 4 of Table II are not approximately constant a poor choice of the starting point has been made.

[12] C. K. Wead, Report of the National Museum for 1900, U. S. Government Printing Office (1902), pp. 417–462.

Mean-Tone Temperament

The Classical System of Instrumental Tuning

WILLIAM BRAID WHITE
The School of Pianoforte Technology, Chicago, Illinois
(Received April 30, 1943)

I. PRELIMINARY

FOR now more than a century, musical instruments of the keyed or valved types, of which the intonation is wholly or partially beyond the performer's control, have been tuned in what is called the "Equal Temperament," whereby the octave is divided into twelve equal semitones, whose frequency ratio is therefore $1 : (2)^{1/12} = 1 : 1.0594631\ldots$.

Equal temperament is a compromise adopted for practical reasons, and particularly because the keyboard pattern of musical instruments had already, by the end of the seventeenth century, become settled in its present form. So long as this keyboard pattern shall be retained, equal temperament is likely to prevail for the tuning of keyboard instruments. Since, moreover, these instruments have come, in practical fact, to dominate the art of music, they have also gradually but irresistibly imposed equal temperament upon that art as a whole, especially in the field of composition; so that the system has come to be taken for granted, and its defects completely ignored by the generality of musicians, while the great world outside professional circles remains almost entirely ignorant that any tuning problem calling for compromise or defect even exists.

TABLE I. Distortions of some musical intervals by equal temperament.

Name of interval	Exact (untempered) frequency ratio	Kind of distortion	Amount of distortion in cents*
Perfect fifth	2 : 3	Narrowed	2
Perfect fourth	3 : 4	Widened	2
Major third	4 : 5	Widened	14
Minor third	5 : 6	Narrowed	16
Major sixth	3 : 5	Widened	16
Minor sixth	5 : 8	Narrowed	14
Harmonic minor seventh	4 : 7	Widened	31
Major seventh	8 : 15	Widened	12
Minor seventh	5 : 9	Narrowed	18

* The "cent" is an artificial interval representing 0.01 equal tempered semitone. Its frequency ratio is, therefore, $1 : (2)^{1/1200} = 1 : 1.0005778$ nearly. The cent is defined in the A.S.A. Standard Acoustical Terminology—Z24..6.12, 1936.

Now, equal temperament gives to the musician complete freedom of modulation (transfer from tonality to tonality) throughout all the combinations possible within a twelve-semitone octave. It treats all such combinations in the same way; and it standardizes, as well as vastly simplifies, both the construction and the playing of keyboard instruments.

These advantages, however, are gained only at the cost of serious defects. Equal temperament allows one and only one interval, the octave, to be tuned exactly. Every other interval is necessarily more or less distorted (made too wide or too narrow). Some of the facts are shown below in Table I.

The distortions shown above are peculiar to equal temperament, and of course they color and psychologically influence the effects of all music performed according to its requirements. Naturally, then, it comes about that when music, written originally in days when another and very different system of intonation was prevalent, and thus essentially determined by that system as to its chordal and general harmonic pattern, is performed, as necessarily happens today, on equally tempered keyboard instruments, it does not sound and cannot in fact sound as its composers expected it to sound and as it sounded to their listeners.

This other system, the immediate predecessor of equal temperament, held the field for some three hundred years, up to the opening of the nineteenth century, before it was superseded completely. For it, our present system of musical notation was worked out, with its foundation of key signatures and relations. It prevailed during the whole of the great formative or classical period of our western music; nor can there be any doubt that its psychological influences, as well as the conditions it imposed upon every kind

of musical composition, were markedly different from that which we have come in these days so completely to accept and to take for granted.

For these reasons, if for no others, it seems worth while once more to set forth an exposition of this classical system of intonation, the famous "Mean-Tone" temperament, and to give likewise some simple and practical directions whereby it may be tuned upon pianofortes and organs. The intonational and therefore the psychological differences of musical effect thus revealed are well worth the attention and study of all who are interested in musical science. The remainder of this paper is devoted to this object.

II. THE FOUNDATION OF TEMPERAMENT

Every musical instrument of which the intonation is either wholly or partially beyond the performer's control during actual playing, calls for some sort of compromise system of intonation. This is due to the fact that no series of successive musical intervals, all of the same rank, however far carried out, can be brought to reach exactly any definite number of octaves. Thus, twelve successive ascending perfect fifths span on the keyboard exactly seven octaves, but in frequency exceed them by almost exactly one quarter of an equally tempered semitone, in fact by 24 cents. The precise ratio is 531441 : 524288, and is usually known as the "Comma of Pythagoras," after its discoverer.

This and the other incommensurabilities are due to the peculiar frequency ratios of the pure musical intervals, themselves derived from the foundation of all western music, the ancient Greek modes, on which have been built up our modern scales, major and minor. Any system of tuning that is to be applied to musical instruments comprising practical, and therefore very limited, numbers of separate sounds within the octave must, therefore, present some compromise with exact intonation. Equal temperament achieves such a compromise by dividing the octave into twelve equal semitones, with results noted in part above (Table I). The predecessor of equal temperament, the mean-tone system, arising at a time when musical thought was strictly confined within the bounds of tonality ("key" and "key-relationship") was necessarily founded on principles less radical, and to that extent of course, less widely applicable. The guiding principle of mean-tone temperament is simple and may simply be set forth.

In order to secure the necessary background for the explanation, it is necessary to call to mind the frequency ratios of the pure diatonic scale (major) which run as shown in Table II. Now, of course, the distinction between the

TABLE II. The pure diatonic scale major, ascending.

		Whole tone	Whole tone	Semi-tone	Whole tone	Whole tone	Whole tone	Semi-tone	
Name	*C*	*D*	*E*	*F*	*G*	*A*	*B*	*C*
Ratios to *C*	1/1	9/8	5/4	4/3	3/2	5/3	15/8	2/1
Ratios, each to the next above it		8/9	9/10	15/16	8/9	9/10	8/9	15/16	

"Whole Tone" and the "Semitone" is familiar to all, based as it is on the pattern of the ancient Greek modes. But the analysis given in Table II shows that actually there are two kinds of whole tone in the pure diatonic scale, bearing, respectively, the frequency ratios, 8/9 and 9/10. These were long ago recognized as distinct, and the names major tone and minor tone were applied to them, respectively. In any system of exact intonation these two kinds of whole tone must exist along with the familiar semitone (15/16).

Evidently, too, the order in which these three intervals appear must always be strictly preserved, unless the character of the pure diatonic scale is to be violently distorted. At this point, therefore, the problem of intonation begins. Every attempt ever made, to fit a system of intonation to both the limitations of the standard keyboard and the requirements of the diatonic scale, has had to take into consideration the major-minor-tone discrepancy. The solution offered by the mean-tone system consists in making its whole tone a mean between, or average of, the major and the minor tones.

III. THE MEAN-TONE SYSTEM

If one tunes, on a keyboard instrument, four exact successive ascending perfect fifths, one arrives at a point two octaves plus one major third above the starting point. But if now, one

reverses the process and tunes downwards again to the starting point, taking, in place of the four perfect fifths, two successive descending exact octaves, plus one exact descending major third, the frequency obtained at the end of the process is found to be 21.50 cents greater than the original frequency, although the two will be identical as to position on the keyboard. One has come back home, but is still, so to speak, standing outside the door. Comparison of the two frequencies thus obtained will show that they stand in the ratio of 81/80. This is seen by the following very simple equation based on the frequency ratios of the fifth (3/2), the major third (5/4), and the octave (2/1):

$$3/2\times3/2\times3/2\times3/2\times1/4\times4/5=81/80.$$

Now, this ratio is exactly equal to the difference between the major tone and the minor tone, since $9/8 : 10/9 = 81 : 80$. This ratio, expressing the difference noted between the two whole tones of the pure diatonic scale, is known as the Comma of Didymus, after its reputed discoverer.

Hence, if one proceeds to tune a scale by narrowing every fifth in the amount of one quarter of this comma, that is by a little less than 5.4 cents, leaving the major thirds and (of course) the octaves exact, one obtains an intonation that makes the whole tone a mean between the major tone and the minor tone of the pure diatonic scale. This is the basis of the classical system of mean-tone tuning.

In passing, it may be noted that, whereas the whole tone ratio of the equal temperament is necessarily the square of its semitone ratio, and, therefore, 1 : 1.122462, the ratio of the mean-tone is the square root of the ratio of the pure major third, which comprises a major tone and a minor tone in succession (e.g., *C-D-E*). This mean-tone ratio is equivalent to 1 : 1.11803.

Mean-tone tuning, as will have been seen involves exactly tuned major thirds. Therefore, the major triads of all tonalities not vitiated by the gaps which mean tone leaves when the standard keyboard alone is available,[1] are sweet and smooth to a very delightful extent. Music written when it was the prevailing system of tuning, was written with the expectation of hearing such chords as have been mentioned, coming out as described, and not as they come out with equal temperament. The character of classical music is entirely altered when heard in this, its original and intended tuning, with results very charming and very revealing.

On the other hand, mean tone, being built, not on artificial semitones but on fifths, requires for its adequate realization more than thirteen keys to the octave. Thus, if one begins to tune descending mean-tone fifths from, say, *A*, in due course one will be called on to tune a fifth descending from *F*. This will be *B* flat. Another fifth tuned downwards from this *B* flat will

TABLE III. Equal temperament and mean-tone temperament compared.

Equal temperament				Mean-tone temperament			
Name		c.p.s.	Cents from *C*	Name	c.p.s.	Cents from *C*	MT–ET cents
C	16	65.40	0	*C* 16	65.40	0	0
	17	69.30	100	*C* sharp	68.83	76	−24
				(*D* flat	70.00)	117	+17
D	18	73.41	200	*D*	73.11	193	− 7
	19	77.78	300	(*D* sharp	76.37)	269	−31
				E flat	78.22	310	+10
E	20	82.40	400	*E*	81.73	386	−14
F	21	87.30	500	*F*	87.45	503	+ 3
	22	92.50	600	*F* sharp	91.37	579	−21
				(*G* flat	93.56)	620	+20
G	23	98.00	700	*G*	97.82	697	− 3
	24	103.82	800	(*G* sharp	102.20)	773	−27
				A flat	104.46	813	+13
A	25	110.00	900	*A*	109.36	890	−10
	26	116.54	1000	(*A* sharp	114.25)	966	−34
				B flat	117.00	1007	+ 7
B	27	123.47	1100	*B*	122.28	1083	−17
C	28	130.81	1200	*C*	130.81	1200	0
	29	138.60	100	*C* sharp	136.66	76	−24
				(*D* flat	140.00)	117	+17
D	30	146.83	200	*D*	146.22	193	− 7
	31	155.56	300	(*D* sharp	152.74)	269	−31
				E flat	156.44	310	+10
E	32	164.81	400	*E*	163.46	386	−14
F	33	174.61	500	*F*	174.90	503	+ 3
	34	185.00	600	*F* sharp	182.74	579	−21
				(*G* flat	187.12)	620	+20
G	35	196.00	700	*G*	195.64	697	− 3
	36	207.65	800	(*G* sharp	204.40)	773	−27
				A flat	208.92	813	+13
A	37	220.00	900	*A*	218.72	890	−10
	38	233.08	1000	(*A* sharp	228.50)	966	−34
				B flat	234.00	1007	+ 7
B	39	246.94		*B*	244.56	1083	−17
C	40	261.62	1200	*C*	261.62	1200	0
	41	277.18	100	*C* sharp	273.32	76	−24
				(*D* flat	280.00)	117	+17
D	42	293.66	200	*D*	292.44	193	− 7
	43	311.12	300	(*D* sharp	305.48	269	−31
				E flat	312.88	310	+10
E	44	329.62	400	*E*	326.92	386	−14
F	45	349.23	500	*F*	349.80	503	+ 3
	46	370.00	600	*F* sharp	365.48	579	−21
				(*G* flat	374.24)	620	+20

Note. The names and frequencies set in parentheses in the mean-tone calculations denote tones that are not available when the tuning is done as set forth in Table IV following. Only one of each pair can, of course, be had. The frequencies are calculated for the standard pitch A_3 = 440 c.p.s.

[1] During the 17th and 18th centuries a few organs were fitted with two or four additional black keys to each octave, but, for obvious technical reasons, the practice was never attempted with stringed keyed instruments such as the harpsichord or pianoforte. See A. J. Ellis: English translation of Helmholtz, *Die Tonempfindungen*, third edition (1895), Appendix XX; also E. F. Rimbault and E. J. Hopkins, *The Organ* (London, 1853, 1877).

give us *E* flat. Now, equal temperament telescopes *B* flat and *A* sharp, *E* flat and *D* sharp, the one into the other. But when the tuning is done by mean tone, *E* flat will simply not do for *D* sharp, (a fifth above *G* sharp) in, say, the key of *E* major; nor will *B* flat as tuned do for *A* sharp (a fifth above *D* sharp) in, say, the key of *B* major. Similar difficulties occur throughout the scale. In fact, Ellis[2] has calculated that, if we include every interval that can be called for in classical harmony, we must have 27 separate sounds to each octave, if intolerable substitutions are to be avoided.

In the circumstances, and considering that the standard keyboard must be used, it is evident that the applicability of mean tone is, and always was, definitely limited. Where it fits in, as with music written with it in mind, the effects it produces are utterly charming compared with what equal temperament give us. Where it does not fit in, it gives excruciatingly harsh intonations, quite intolerable. The tuners of the mean-tone days used to discuss gravely where they should place the "wolf," that is, the worst discrepancy. Usually this was placed at the point where *A* flat must be tuned and must sometimes be used for *G* sharp. In the case mentioned, *G* sharp would come out 40 cents flatter than *A* flat. The resulting beating was then compared with the howling of wolves: Hence the name "wolf," applied to this intolerably bad place in the scale.

In Table III the frequencies given by mean tone have been compared with the equal tempered frequencies over a distance of two octaves and a half. The mean-tone frequencies include both sharps and flats, but not double sharps, double flats, or enharmonics like *B* sharp, *C* flat, *E* sharp, or *F* flat. Enough has been given, however, to show the nature of the differences between the two systems. The mean-tone distances in cents are taken without further ado from Ellis[2] but may be arrived at independently from the data already given. The frequencies have been calculated by the writer. An equal tempered fifth spans 700 cents, an exact fifth 2 cents more or 702. A mean-tone fifth spans 697 cents.

[2] A. J. Ellis, English translation of Helmholtz, *Die Tonempfindungen*, third edition (1895), Appendix XX.

TABLE IV. Scheme for tuning in mean-tone temperament on a standard keyboard, using thirteen sounds inclusive within the octave (After Hurren). (The frequencies used are taken from Table III.)

First series				Beats per second
1. Tune *C* 40 (Middle *C*) to tuning fork, 261.62 c.p.s.				
2. Tune *C* 28 to *C* 40	Octave	Down	Exact	0
3. Tune *G* 35 to *C* 28	Fifth	Up	Narrow	1.15
4. Tune *D* 42 to *G* 35	Fifth	Up	Narrow	2.10
5. Tune *D* 30 to *D* 42	Octave	Down	Exact	0
6. Tune *A* 37 to *D* 30	Fifth	Up	Narrow	1.20
7. Tune *E* 44 to *A* 37	Fifth	Up	Narrow	2.35
8. Tune *E* 32 to *E* 44	Octave	Down	Exact	0
9. Tune *B* 39 to *E* 32	Fifth	Up	Narrow	1.25
10. Tune *F* sharp 46 to *B* 39	Fifth	Up	Narrow	2.72
11. Tune *F* sharp 34 to *F* sharp 46	Octave	Down	Exact	0
12. Tune *C* sharp 41 to *F* sharp 46	Fifth	Up	Narrow	1.58
13. Tune *C* sharp 29 to *C* sharp 41	Octave	Down	Exact	0
Second series				
1. Tune *F* 33 to *C* 40	Fifth	Down	Narrow	1.46
2. *B* flat 26 to *F* 33	Fifth	Down	Narrow	1.20
3. Tune *B* flat 38 to *B* flat 26	Octave	Up	Exact	0
4. Tune *E* flat 31 to *B* flat 38	Fifth	Down	Narrow	1.32
5. Tune *A* flat 24 to *E* flat 31	Fifth	Down	Narrow	0.5
6. Tune *A* flat 36 to *A* flat 24	Octave	Up	Exact	0

Note. The average beat rate of the fifths in the first series is very nearly 2 per sec. (more closely 7 in 4 sec.); and in the second series a very little more than 1 per sec. (more exactly 9 in 8 sec.). If the fifths are tuned, as nearly as can be managed, to these average rates, the result will be quite satisfactory for ordinary purposes.

IV. PRACTICAL METHODS FOR TUNING IN MEAN TONE

Subject to the limitations exhibited in the preceding discussion, the simplest method of tuning in mean tone is, of course, to make use of the chromatic stroboscope of C. G. Conn, Ltd., that has been described more than once in this Journal. It is only necessary to select the sounds to be used for the keyboard, as, for example, those selected in Table III, and then, by setting the frequency control to the proper cents figure in each case, to tune accordingly. When this is not available, it is best to adopt the method used by the old mean-tone tuners, who worked entirely by fifths and octaves. Ellis[2] prescribes a circle of alternate fourths and fifths, such as is used by tuners today working in equal temperament; but what follows is probably quite as likely to produce fairly accurate results. The tuning of correct octaves is not easy, but there will be little difficulty in arriving at tolerable narrowing of the fifths, according to the beat rates noted in Table IV. The actual series here used are taken from a report of the *Proceedings of the Institute of Musical Instrument Technology* (London, 1942), describing a demonstration of mean-tone temperament by S. A. Hurren. Acknowledgments are due and

are tendered. The beat rates have been calculated by the writer, who has been greatly aided by the tables of cents related to frequency, compiled by Robert W. Young of C. G. Conn, Ltd., makers of the chromatic stroboscope.

The tuning is done in two series or circles, one from *C* 40 to *C* sharp 41 by fifths up and octaves down; the other from *C* 40 to *A* flat 36 by fifths down and octaves up. In the first series the fifths are narrowed by first tuning as exactly as possible and then depressing the upper member of the interval to the required beating. In the second series, where the fifths are taken down, the lower member of the interval is of course raised instead of being lowered.

It will be noted, of course, that the first series gives us *F* sharp, but not *G* flat, *C* sharp but not *D* flat. The second circle yields *B* flat but not *A* sharp, *E* flat but not *D* sharp, and *A* flat but not *G* sharp. Here lies the weakness of mean tone, as applied to a thirteen-to-the-octave keyboard. The equal temperament telescopes the discrepancies and thus evades the difficulties, although at the cost of other defects.

Nevertheless, as everyone will testify who has made the trial, the mean-tone tuning is better fitted for the performance of music that was written when it stood as the prevailing system of tuning; and that of course comprises the music of the whole classical age, from Tallis and Byrd to Mozart and Beethoven. It is certain that equal temperament does not represent the last, even if it certainly comprises the latest, word that may be said on the subject of musical intonation. As the art of music continues its development, the questions that equal temperament leaves unanswered will persistently press for attention. Meanwhile the present paper, by directing attention once more to the system that for so long held the field and that formed the foundation of the most splendid achievements in musical composition yet brought to being, may do something to uncover a fascinating and fruitful region of research and discovery.

Supersonic Measurements in CO_2 and H_2O at 98°C

W. H. PIELEMEIER AND W. H. BYERS
The Pennsylvania State College, State College, Pennsylvania

(Received May 21, 1943)

Measurements with CO_2 at 98°C were made with the hope that the minor absorption peaks found earlier at 28°C might be made more prominent. At the higher temperature the CO_2 holds more water vapor thus furnishing a longer range of relaxation times. The control and measurement of temperature and humidity were improved. Otherwise the procedure was that used at 28°C. The apparent change in relaxation times from 28°C to 98°C was not entirely the expected one and the minor absorption peaks were not as prominent as we hoped they would be. The velocity at high frequency and the change in velocity through the dispersion region and also the total absorption were found approximately as expected. The specific heat of CO_2 calculated from our results agrees much better with the values calculated from spectroscopic data and with the most reliable calorimetric results than do the values obtained by some earlier investigators who used the velocity or the absorption of sound waves.

INTRODUCTION

ABSORPTION and velocity measurements on supersonic waves in CO_2-H_2O mixtures at 28°C by Pielemeier, Saxton, and Telfair[1] seem to indicate *two* absorption and dispersion regions for each gaseous mixture. The data suggest that the *smaller* absorption and dispersion might be associated with the longitudinal (or valence) mode of vibration within the CO_2 molecules. They suggest also that as the H_2O concentration approaches zero both regions shift to lower frequency, each in a linear manner, and that they appear nearly to merge for dry CO_2. The rate of shift found by Knudsen and Fricke[2] at 23°C when given in terms of *mole* percent H_2O is only slightly greater than the rate[1] for the larger absorption and dispersion at 28°C. The above data[1] are not entirely conclusive because a *theoretical absorption* curve plotted on the basis of two relaxation times related to the energy levels as listed yields a smaller secondary peak than that observed. The absorption peaks obtained by both Leonard[3] and Fricke[4] using very dry CO_2 appear as if the two peaks were not quite merged into one, the major peak being near 30 kc and the minor near 40 kc by Leonard and near 17 kc and 37 kc by Fricke.

As higher temperatures will cause the valence mode to contribute relatively more to the internal energy of the molecules and as larger mole fractions of water vapor are also possible at higher temperatures it was decided to repeat the measurements[1] using 98°C instead of 28°C.

EXPERIMENTAL METHOD

The apparatus used is that described by Telfair and Pielemeier[5] with a minor addition to determine more accurately the water vapor content of the carbon dioxide. The carbon dioxide was obtained from dry ice and passed through a humidifier consisting of two lines in parallel. (We and others have found the gas from properly manipulated dry ice as good as any other CO_2 obtainable.) One line contained P_2O_5 drying tubes, while the other contained bubblers immersed in a thermostated water bath. Thus water vapor contents below the vapor pressure of water at 0°C could be easily obtained by regulating the rate of flow in the two parallel lines. The carbon dioxide entered the supersonic chamber near the bottom and flowed out through a tube near the top. The emergent gas then passed through a General Electric Dew-Point potentiometer in order to measure the water vapor pressure. This was then reduced to the mole percent water in the mixture. In this way the gas was flowing quite slowly but steadily while the supersonic measurements were made. In

[1] W. H. Pielemeier, H. L. Saxton, and D. Telfair, J. Chem. Phys. **8**, 106 (1940).
[2] V. O. Knudsen and E. Fricke, J. Acous. Soc. Am. **12**, 255 (1940).
[3] R. W. Leonard, J. Acous. Soc. Am. **12**, 241 (1940).
[4] E. F. Fricke, J. Acous. Soc. Am. **12**, 245 (1940).
[5] D. Telfair and W. H. Pielemeier, Rev. Sci. Inst. **13**, 122 (1942).

order to allow the walls of the chamber to reach equilibrium with the water content of the gas, the gas was allowed to flow for some time until the Dew-Point potentiometer indicated that the emergent gas had a constant humidity. (Before the gas was admitted to the chamber at all, the latter was, of course, evacuated.) The dew-point of the carbon dioxide was checked several times during each run and was always found to be constant to within a degree or two Fahrenheit.

The order in which the data were taken might affect the results if a systematic equilibrium lag occurred between the water in the gas and that adsorbed on the chamber walls. The 442.8-kc and the 549.8-kc data were taken almost at random humidities; while the 614.6-kc data were taken starting at 2.98 percent water vapor and running to dry carbon dioxide, then beginning at 3.14 percent and running up to 4.02 percent. The two sections of the plotted results joined nicely. Thus any effect of the adsorption of water on the walls is thought to be absent.

Temperature was measured on two copper-constantan thermocouples carefully calibrated against a standardized couple of the Petroleum Refining Laboratory of this college. They were located at different levels in the gas chamber, and the heat from an auxiliary heating element in the surrounding oven was adjusted to make the couples indicate like temperatures. Thus in the small distance used, there was only a negligible temperature gradient possible. A hollow cylinder of copper lined the supersonic chamber to help equalize the temperature. These extreme precautions were taken because H_2O and temperature are the two chief factors determining the velocity at a given frequency.

The absorption coefficient per wave-length (μ) was obtained from the logarithmic decrement of the plate current peak heights ΔI_P plotted as a function of the resonance peak number. The resulting curve was in every case a straight line. The observed value of μ is a function of twice the amplitude decrement and is given by the equation

$$\mu = 2(2.303)\left[\frac{\log (I_P)_A - \log (I_P)_B}{n_A - n_B}\right] = 4.61(-\text{slope}).$$

The conditions developed by Hardy* for the validity of this equation were fulfilled in each case.

THEORETICAL CALCULATIONS

The internal specific heat due to the vibration of the carbon dioxide molecule was calculated from the frequencies of vibration given by Sponer[6] and the equations given by Pielemeier, Saxton, and Telfair.[1] It was necessary to use up to the 4th quantum state of the deformation mode, to the 2nd state of the symmetrical valence mode, and only the 1st state of the unsymmetrical valence mode of vibration. The results follow:

Mode	C_i(370.1°K)	C_i(371.0)
$^2\delta\perp$	2.231	2.237
$\nu_i\|\|$	0.300	0.302
$\nu_u\|\|$	0.016	0.016
Total	2.547	2.555 cal./mole

Considerable difficulty was encountered in obtaining reliable constants to use in theoretical calculations of the absorption coefficients, and in calculation of velocities in dry carbon dioxide of supersonic waves at the frequencies and at the temperature used. Primarily, it is necessary to know the ordinary (equilibrium state) value of the specific heat at constant volume (C_0). The reported values of this constant and of data from which it may be calculated are quite conflicting. Values of C_p have been found in the literature ranging from 8.94 cal./mole[7] through 9.11 cal./mole[8] to 9.70 cal./mole.[9]

If it is desired to calculate the specific heat from velocity of sound measurements, it is necessary to be sure that the full specific heat is still effective; that is, that a sufficiently low fre-

* H. C. Hardy in his Doctorate Dissertation, The Pennsylvania State College (1941), developed the requirement that $\frac{\Delta I_P}{I_P} < 0.03$ and that $2\mu n_A > 5.0$ and $\mu n_B > 5.0$, n_A and n_B being the number of half-wave-lengths from the source at the two respective peaks. The great absorption in CO_2 and Hardy's requirements usually made it impossible to use more than 15 to 20 resonance positions of the reflector. The results of these were so consistent, however, that the uncertainty remained small.

[6] H. Sponer, *Molekulspecktren* (Springer, 1935), Vol. I, p. 75.

[7] S. K. K. Jatkar, J. Ind. Inst. Sci. **22A**, 93 (1939).

[8] F. E. King and J. R. Partington, Phil. Mag. [7] **9**, 1020 (1930).

[9] A. Eucken and v. Lüde, Zeits. f. physik. Chemie **B5**, 413 (1929).

quency has been used. To be sure of this, the location of the velocity dispersion region (obtainable from a value of the relaxation time) must be known. Here again contradictions were encountered. When Richards and Reid's[10] measured velocities of 9-kc sound in pure carbon dioxide are extrapolated beyond their 90°C value to 100°C, either by the method of least squares or graphically, a result of 298.9 meters per second is obtained. They believed that dispersion had already begun; but Jatkar[7] gives good opposing evidence and King and Partington[8] give 300.1 meters per second as the velocity of 3-kc sound at 100°C. However, Eucken and Becker[11] at 75°C and 58.4 kc give a velocity of 297.3 meters per second, while a graphical interpolation of van Itterbeek and Mariens'[12] data at 598.99 kc gives at 75°C a velocity of 303.2 meters per second. Eucken and Becker's value together with Richards and Reid's 9-kc value of 289 meters/second at 75°C would locate the dispersion region in the neighborhood of 40 to 50 kc; a fact which is not supported by the relaxation times given by van Itterbeek and Mariens. Küchler[13] gives the following data for the relaxation times:

t°C	19	100
$\beta_{atmos}\times 10^6$	6.0	4.8

while Itterbeek and Mariens give (when extrapolated from 80°C):

t°C	19	100
$\beta_{atmos}\times 10^6$	11.6	8.0*

If there is but a single dispersion region in dry carbon dioxide, the inflection point would then be located as shown:

by Küchler at 45 kc (100°)
by Itterbeek at 28 kc (100°).

The inflection points at room temperature would agree qualitatively with Richards and Reid's findings of too large a value of V_0 at this temperature when 9-kc sound is used.

[10] W. T. Richards and J. A. Reid, J. Chem. Phys. **2**, 193 (1934).
[11] A. Eucken and R. Becker, Zeits. f. physik. Chemie **B27**, 235 (1934).
[12] A. van Itterbeek and P. Mariens, Physica **7**, 909 (1940).
[13] L. Küchler, Zeits. f. physik. Chemie **B41**, 199 (1938).
* The value at 100°C is very uncertain but this is the lowest that the data will permit.

The result of all this confusion is that no completely independent theoretical check on the results of the experiments herein reported could be obtained. So the author resorted to the following process: In view of the low frequency[3,12] of the inflection point of the dispersion curve for dry CO_2, it was felt that at the frequencies used the vibrational specific heat was almost completely inactive in dry carbon dioxide. Therefore, the average of the velocities obtained by extrapolating from 0.1 (or less) percent water vapor to dry carbon dioxide at four frequencies, namely, 313.4 meters per second, was taken as V_∞. This value may be justified by the fact that when Itterbeek and Mariens' measured velocity values for 598.99 kc are extrapolated from 89°C to 98°C a value of 313.4 meters per second is obtained. Then using the velocity equation developed by Hardy[14] and the Beattie-Bridgeman equation of state,[15] C_∞ was found to be 4.933 calories per mole. (C_∞ refers to the specific heat at constant volume effective in sound waves of very high frequency, or to be observed when no vibrations are excited within the molecule.) From this, C_0, given by $C_\infty+C_i$, was found to be 7.488 calories per mole. This value agrees well with 7.527 found from C_0^∞, the specific heat at infinite volume, by the method of Hardy[14] when C_0 is taken as $(3/2)R+(2/2)R+C_i$. Having C_0, the velocity equation was again used to get V_0. The result was 297.5 meters per second. An experimental check on this last value may be made with the result of extrapolating Richards and Reid's measured velocities to 98°C. The result is 298.0 meters per second. The difference is 0.5 meter per second. Jatkar[7] cites evidence that 9 kc gives V_0 correctly.

Having now a value of C_0, the absorption coefficient per wave-length was calculated by means of the formula

$$\mu_m = RC_i/[C_0(C_0+R)C_\infty(C+R)]^{\frac{1}{2}}.$$

In obtaining values of μ to compare with experimental results, the above μ_m was increased by twice the classical absorption (μ_c) due to heat conduction and viscosity. This is in accord with

[14] H. C. Hardy, D. Telfair, and W. H. Pielemeier, J. Acous. Soc. Am. **13**, 226 (1942).
[15] J. A. Beattie and O. C. Bridgeman, J. Am. Chem. Soc. **49**, 1665 (1927).

results found by Pielemeier, Saxton, and Telfair[1] and other workers, but not by Pumper[16] who attributes the excess to scattering by dispersion.

RESULTS

The theoretical and experimental results are given in Table I and one of the curves from which the experimental results were taken follows. In the table "μ_m" refers to the absorption coefficient per wave-length calculated on the assumption

TABLE I. Absorption measurements.

frequency	442.8 kc	549.8 kc	614.6 kc
temperature	97.3°C	97.0°C	97.9°C
pressure	73.5 cm	73.5 cm	73.5 cm
% H_2O for	0.76±.06	0.92±.06	0.98±.1
μ (obs.)	0.354±.01	0.344±.01	0.344±.01
$\mu_m+2\mu_c$ (calc.)	0.334	0.335	0.338
$\mu_\delta+2\mu_c$ (calc.)	0.294	0.296	0.298
μ_c	0.005	0.006	0.007

that all the modes of vibration have the same relaxation times; "μ_δ" is that calculated for the deformation mode alone; "μ_c" is the classical absorption for carbon dioxide plus the proper amount of water vapor.

In Table II all velocities were corrected to 98.0°C; the temperature for the measurements varied from 97 to 98°C. "V_0" is the low frequency velocity, calculated as above described. "V_∞" is the high frequency velocity. "ΔV" is the total dispersion, whose *calculated* value was obtained by subtracting the calculated V_0 from 313.4 m/sec., the average observed V_∞; and whose *observed* value was found by subtracting the observed V_0 from the observed V_∞. The observed value of V_0 was obtained from Pielemeier's Fig. 1, next article, and by noting how far the velocities at high humidities come from running asymptotic to a velocity *vs.* humidity curve calculated on a classical density and specific heat change and based on $V_0=297.5$ meters per second. This is the dashed straight line on Fig. 1. "ΔV_δ" is the dispersion due to the deformation mode alone, and was calculated by the equation

$$V_\delta^2 = V_0^2[RC_i/(C_0+R)C+1],$$

using for C_i merely the portion of it due to the deformation mode. Then

$$\Delta V_\delta = V_\delta - V_0.$$

[16] E. J. Pumper, J. Phys., U. S. S. R. **1**, 411 (1939).

DISCUSSION OF RESULTS

When the measured velocities are extrapolated the very short distance from $h=0.1$ percent to $h=0$ to obtain the velocity V_∞ in *dry* CO_2, the values at these four frequencies suggest a slight dispersion. However, because of the curvature of the velocity *vs.* humidity curves in this region for all except the 1593-kc case, this progressive increase in V_∞ with frequency may have little significance. Hence this effect will be neglected. A slight extra weight might have been given the observed 313.7 m/sec. at 1593 kc to obtain an average of 313.5 m/sec. as this frequency is so high that the extrapolated value should be about the same as the observed one.

As to V_0 values it might be said that in no case do the curves actually reach the dashed line which passes through the *calculated* V_0 at $h=0$. However, the curves are still approaching this dashed line which represents the *calculated* low frequency velocity as a function of h. (See Fig. 1.) Hence it is felt that they would reach it at higher humidities. The parallel solid line passes through the *observed* V_0 at $h=0$. (See the V_0 curve in Pielemeier's Fig. 1, next article.)

The progressive change in shape of the absorption curves as we go to higher frequency suggests that at the lowest frequency a second (but smaller) peak might be merged rather closely

TABLE II. Velocity measurements in dry CO_2 in meters/second.

frequency	442.8 kc	549.8 kc	614.6 kc	1592.8 kc
pressure	73.4 cm	73.3 cm	73.4 cm	73.7 cm
V_∞ (obs.)	313.1±.3	313.2±.3	313.4±.3	313.7±.2
V_0 (obs.)	298.2	298.0 (or less)	298.4 (or less)	
V_0 (calc.)	297.5	297.5	297.5	
ΔV (obs.)	15.2	15.4 (or more)	15.0 (or more)	
ΔV (calc.)	15.9	15.9	15.9	
ΔV_δ (calc.)	13.9	13.9	13.9	

with the first and that at the highest frequency (see *A* and *B*, Fig. 1) the merging tendency has diminished. This effect was predicted in an earlier article[1] and it and other items will be discussed in the accompanying article by Pielemeier where the results of this investigation are plotted in his Fig. 2. In our Fig. 1 the dotted line represents the expected μ curve if the major peak only were present.

The larger observed value of μ_m with the lowest

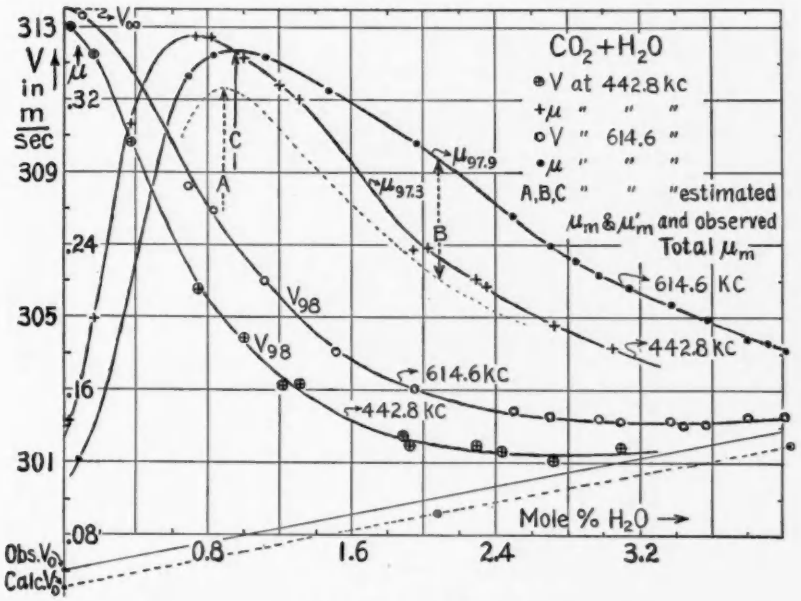


FIG. 1. μ and μ' stack higher at the 442.8-kc peak because A and B for it are closer together.

frequency suggests more perfect stacking of two peaks to form the resultant one than is the case with the other frequencies.

A few measurements were made with 99.97 percent pure helium in order to check our measured results with theoretical values obtained for a gas having *translational* specific heat only. The velocity at 24.9°C fits the curve which we plotted using van Itterbeek's[17] data. The observed absorption was twice μ_c.

The work of Eucken and van Itterbeek was discussed in an earlier article.[7] Since its publication they have published important articles which are discussed in Pielemeier's accompanying article. Schäfer's[18] work puts our earlier predictions[1] on a firmer theoretical basis.

In conclusion it may be stated that our results on velocity at 98° came up to expectations but those on absorption did not. Instead of the minor peak's expected greater prominence the two peaks were shifted and merged enough to make the minor one *less* prominent.

[17] A. van Itterbeek and P. Mariens, Physics **7**, 938 (1940).

[18] K. Schäfer, Zeits. f. physik. Chemie **B46**, 212 (1940).

Supersonic Measurements in CO_2 at 0° to 100°C

W. H. PIELEMEIER
Department of Physics, The Pennsylvania State College, State College, Pennsylvania
(Received May 29, 1943)

Previous measurements are reviewed and curves are drawn for the velocity of low frequency and of high frequency sound waves in dry CO_2 as functions of the temperature from 0 to 100°C. Another set of curves shows how the frequency producing maximum absorption per wave-length depends on the water vapor concentration in the CO_2 at approximately one atmosphere pressure. Evidence is presented for two distinct relaxation times for each given concentration. Acetaldehyde is cited as a gas in which three relaxation times have definitely been found. Our recent measurements of the velocity at 98°C check well with the curve but the evidence for two distinct relaxation times was not more definite than at 28°C.

THE PURPOSE OF THIS STUDY

CONSIDERABLE data on velocity and absorption in CO_2 have been obtained during the past eighteen years. Many of the results seem to conflict. This study attempts to harmonize the best values. Graphs are drawn and evidence of two relaxation times is presented. A number of investigators state that they have found no such evidence.

In our other article in this issue[1] W. H. Byers and I point out that values of C_p in CO_2 at about 98°C have been found in various reports ranging from 8.94 cal./mole at 97.1°C[2] to 9.70 cal./mole at 98°C.[3] Since the value of C_p is involved in the calculation of the theoretical values of V, the velocity of sound waves in CO_2, and also of μ_m, the maximum absorption per wave-length, the available reports on sound waves in CO_2 were reviewed rather carefully. Some of the published results are plotted in Fig. 1. Curves for V_∞ and for V_0 as functions of the temperature in dry CO_2 are shown in this figure. V_∞ and V_0 designate the velocity at very high and at very low frequency, respectively. In the case of V_∞ the acoustic period is so short that the periodic changes in the internal vibrational heat constant cannot remain in phase with the other periodic changes occurring as the sound wave passes through the gas. In the case of V_0 they do remain essentially in phase and the full values of C_p and C_v are effective. In the opinion of the author the curves of Fig. 1 set rather narrow limits of uncertainty for V_∞ and V_0. They should also limit the uncertainty in the specific heat values. The approximate value of μ_m at any temperature within the range 0 to 100°C can be obtained from this chart by the equation

$$\mu_m=\pi\frac{V_\infty-V_0}{V_\infty V_0}\Big[=3.14\frac{98200-88850}{298.0(313.5)}$$
$$=(0.313\pm0.01)\text{ at }98°\text{C}\Big]. \quad (1)$$

Since

$$V_0^2=\frac{C+R}{C}\frac{RT}{M}\Phi^2 \quad \text{and} \quad V_\infty^2=\frac{C_\infty+R}{C_\infty}\frac{RT}{M}\Phi^2$$

this yields

$$\mu_m=\pi RC_i/[C(C+R)C_\infty(C_\infty+R)]^{\frac{1}{2}}$$
$$[=0.324\pm0.01\text{ at }98°\text{C}], \quad (2)$$

in which R is the gas constant (1.9868 cal./mole/degree K), C_i is the internal specific heat in cal./mole, $C=C_v$ is the specific heat at constant volume in cal./mole, $C_\infty=C_v-C_i$, T is the absolute temperature in degrees Kelvin, Φ is the correction factor[4] for Van der Waals forces and is approximately equal to Richards'[5] $1/w$. By using the approximations $CC_\infty \doteq C_x^2$ and C^2C_∞

[1] W. H. Pielemeier and W. H. Byers, J. Acous. Soc. Am. **15**, 17 (1943).
[2] S. K. K. Jatkar, J. Ind. Inst. Sci. **22A**, 93–110 (1939).
[3] A. Eucken and V. Lüde, Zeits. f. physik. Chemie **B5**, 413 (1929).
[4] D. C. Miller, *Sound Waves, Their Shape and Speed* (Macmillan Company, New York, 1937), p. 150. Note: He *used* the value of Φ^2 instead of Φ as it appears.
[5] W. T. Richards and J. A. Reid, J. Chem. Phys. **2**, 193 (1934).

$$\doteq CC_\infty^2 \doteq C_x^3$$

$$\mu_m = \pi RC_i/(C+R)C_\infty \left[= \frac{3.14(1.9868)(2.555)}{9.169(4.933)} \right.$$

$$\left. = (0.325 \pm 0.01) \text{ at } 98°\text{C} \right]. \quad (3)$$

The observed μ_m when corrected for viscosity and heat conduction (observed $\mu_m - \mu_c$) still exceeds these calculated values in Eqs. (1) and (2) by about 0.01. Pumper[6] finds what he terms *scattering* to be responsible for about 0.01 with some of his quartz plates.

The numerical values substituted in Eq. (1) are obtained from Fig. 1. Most of the other numerical values are taken from our other article.[1] It is interesting to note that the value of μ_m calculated from spectroscopic and thermodynamic data [Eq. (2)] lies midway between the value calculated from observed velocities [Eq. (1)] and the average value of [(observed

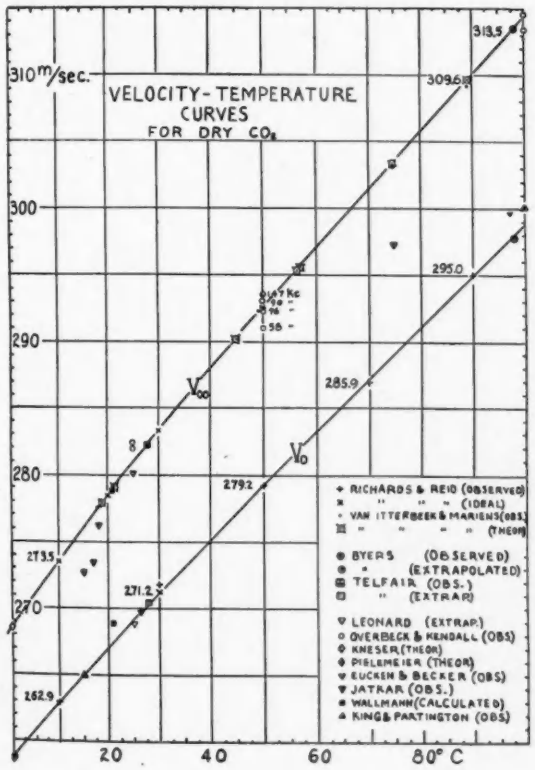


FIG. 1. Good up to $h \doteq \frac{1}{4}$ percent but f_m increases with h as in Fig. 2.

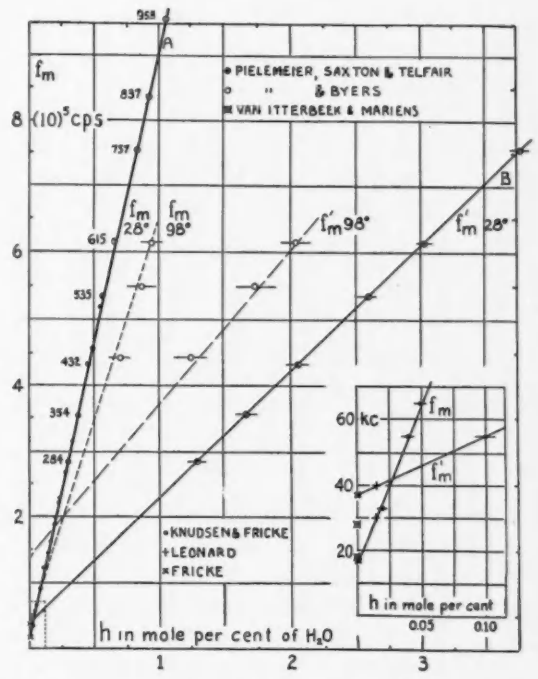


FIG. 2. Frequency f_m at which a selected humidity produces maximum absorption (or dispersion).

$\mu_m) - \mu_c]$ where $\mu_c \doteq 2\mu_c$,[1] namely:

From observed V_0 and V_∞, $\mu_m = 0.313 \pm 0.01$.

The theoretical $\mu_m = 0.324 \pm 0.01$.

The average directly observed

$$(\mu_m - \mu_c) = 0.335 \pm 0.01 \left[= \frac{0.344 + 0.332 + 0.330}{3} \right].$$

Figure 2 represents an attempt to establish more firmly the evidence for two relaxation times in CO_2 and to show how these vary with the H_2O concentration at room temperature and at 98°C. The relaxation time τ and the lifetime β of a quantum are inverse functions of f_m, the frequency for maximum absorption.

SELECTION OF THE BEST DATA TO PLOT

In drawing the curve for V_∞, Fig. 1, the theoretical values given by van Itterbeek[7] were used because they formed the most complete set of reliable values and because they are accompanied by his almost identical *measured* values. It should be noted how well the points furnished by the

[6] E. J. Pumper, J. Phys. U.S.S.R. 1, 411 (1939).

[7] A. van Itterbeek and P. Mariens, Physica 7, 909 (1940).

work of Richards and Reid,[5] Telfair,[8] Wallmann,[9] Byers,[1] and Overbeck and Kendall[10] fit this curve. Extrapolations applied to the work of Leonard,[11] Kneser[12] and others fit the curve quite well also. Some of the frequencies used by Overbeck and Kendall are in the dispersion region thus bringing such points below V_∞. No points should appear above V_∞. Probably temperature gradients are chiefly responsible for the few thus shown.

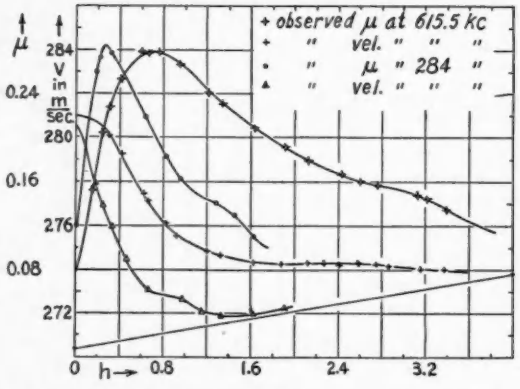


FIG. 3. Velocity and absorption curves at two frequencies in CO_2-H_2O at 28°C. The solid straight line begins at the observed V_0 obtained from Fig. 1. With increasing values of the mole percent H_2O concentration h, the density of the mixture decreases and V_0 increases. The major and the minor peaks are nearer together at the lower frequency. (Figure 3, reference 8, without dotted line.)

The curve for V_0 was drawn through points furnished by the work of Richards and Reid.[5] They obtain their value for the "ideal" low frequency velocity at 30°C from spectroscopic data. The curve is drawn through this point and approximately through their observed points for the velocity of 9-kc waves. They state that the CO_2 was not quite pure. This may account for the position of their observed point for 30°C. Nevertheless, these points were used because they are the most extensive of the reliable sets and because they are in good agreement with the writer's theoretical values and with the experimental or theoretical work of Jatkar,[2] King and Partington,[13] Telfair,[8] Byers,[1] Sherrat and Griffiths,[14] Torman, Kaye and Sherrat, Partington and Howe, Shilling, Pennman, Kneser, Dixon Campbell and Parker, and others. No points should come appreciably below V_0. Observed points which do this probably result from errors in temperature, frequency, or wave-length. Many reliable measurements have been made for conditions which place the velocity between V_0 and V_∞, i.e., in the dispersion region. The frequency range falling in the dispersion region is determined by the H_2O concentration and also by the temperature and pressure. The author feels confident in stating that velocity values which fall considerably outside the region between these curves must involve incorrect measurements. Since temperature is the chief determining factor of V_0 and V_∞ and since it is so difficult to prevent temperature gradients, especially if the gas is far from room temperature, this is probably the chief source of error. Since one-tenth of one percent water vapor in the CO_2 increases the dispersion frequency by 88 kc the exact determination of the vapor content is important also. However, this should not result in a velocity above V_∞ nor below V_0.

Line A in Fig. 2 can be determined with high precision because the large number of points shown fall approximately on a straight line. Several of Telfair's[8] points which extend the line up to 1600 kc are omitted here so as to use a more convenient scale for f_m. The inset magnifies the area within the dotted rectangle near the origin, so as to show the points furnished by the work of van Itterbeek,[7] Knudsen and Fricke,[15] Leonard,[11] and Fricke[16] to better advantage. Fricke's 17-kc and van Itterbeek's 18-kc values for f_m in dry CO_2 at room temperature and pressure locate the intercept with precision. The latter's 28-kc value for 100°C may be more uncertain. Leonard[11] considered his CO_2 to be dry but when his results are plotted as shown there is a strong suggestion that the humidity was about 0.015 mole percent. This is suggested also by the larger value of μ_m which will be discussed later.

The line B of Fig. 2, showing f_m' values for 28°C, was drawn approximately through our six

[8] W. H. Pielemeier, H. L. Saxton, and D. Telfair, J. Chem. Phys. **8**, 106 (1940).
[9] v. M. H. Wallmann, Ann. d. Physik **21**, 671 (1934).
[10] C. J. Overbeck and H. C. Kendall, J. Acous. Soc. Am. **13**, 26 (1941).
[11] R. W. Leonard, J. Acous. Soc. Am. **12**, 241 (1940).
[12] H. O. Kneser, Ann. d. Physik **11**, 777 (1931).
[13] F. E. King and J. R. Partington, Phil. Mag. [7] **9**, 1020 (1930).
[14] G. G. Sherrat and E. Griffiths, Proc. Roy. Soc. London **156**, 504 (1936).
[15] V. O. Knudsen and E. Fricke, J. Acous. Soc. Am. **12**, 255 (1940).
[16] E. F. Fricke, J. Acous. Soc. Am. **12**, 245 (1940).

points and the three shown in the magnified inset. The latter were obtained from the work of the three authors named in Fig. 2.[11, 15, 16]

The dotted lines for 98°C are rather uncertain especially the one for f_m' at 98°. An approximate value of f_m for dry CO_2 at 98° can be estimated by noting the frequency whose logarithm lies about midway between log 9 kc[5] and log 442 kc.[1] These frequencies seem to be near the two ends of the dispersion region at 98°. (See Fig. 1.) This gives about 47 kc and van Itterbeek's[7] β-value yields about 28 kc. (See Fig. 2.) There seems to be a tendency for the major and minor peaks to merge together at the two lower frequencies. Schäfer[17] discusses such a tendency.

The velocity measurements in *air* by Hubbard and Zartman[18] were also plotted as a function of temperature. The 331.7 m/sec. value for 0°C when corrected for frequency dispersion and for 0.03 percent CO_2 gives 331.5 ± 0.2 m/sec. which is in excellent agreement with the value we published last year.

EVIDENCE OF TWO RELAXATION TIMES

Schäfer[17] has shown that a fairly smooth dispersion or absorption curve does not necessarily signify the absence of multiple relaxation times. Hence any evidence of an extra peak or hump in such curves becomes positive evidence for an extra relaxation time. He points out that some of our velocity values shown in Fig. 3[8] fall below the dotted line for low frequency waves. The V_0 curve in Fig. 1 of the *present* article shows that our dotted line is 0.5 m/sec. too high. At that time we used the value measured at 30°C by Richards.[5] This happens to be the poorest point of his entire set. Our new straight line fits our lowest points very well. Schäfer also points out that our theoretical velocity and absorption curves show the minor humps less prominently than do the observed points. For convenience our former Fig. 3[8] is shown here with the corrected V_0, but without the theoretical curves. It might be stated that our theoretical absorption curves were obtained by using only the observed wave numbers listed in our Fig. 7.[8] If all the energy levels given by Leonard[11] are used with the proper assignment as to relaxation times, the agreement is much better. The minor peak height seems to be between 0.1 and 0.2 of the major peak height. If such an assignment had been made by Leonard and Fricke[16] it would seem less arbitrary and their unequal peak heights would be explained as due to less perfect stacking of the *two* peaks when $h=0$, as it apparently was for Fricke's data. The greater separation of the f_m and f_m' curves for $h=0$ would lead us to expect this. For convenience Fricke's absorption curve for dry CO_2 is reproduced in Fig. 4 to show why his f_m and f_m' values were selected as shown in Fig. 2. We have drawn a dotted curve through his observed points and have considered this as the resultant of two others, one of which is shown with its peak at 17 kc. The latter has the correct theoretical form for a maximum of 0.215 due to a single lifetime. Then the vertical separation of the two curves represents μ' which has its peak at about 37 kc ($\mu_m' \doteq 0.2\mu_m$). In a similar way Leonard's peaks fall at 30 and 40 kc and have more nearly merged into one.

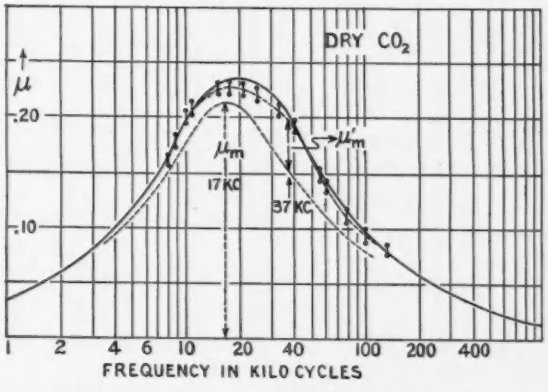


FIG. 4. (Fricke's Fig. 6. Curve showing the absorption per wave-length for CO_2. The maximal absorption occurs at 20 kc and μ_{max} has the value of 0.230.) The dotted peak at 17 kc is Pielemeier's estimate of the major peak alone. It and the minor peak at 37 kc together give a curve fitting Fricke's observed points better than any symmetrical bell-shaped curve with a *single* peak.

To check the crossing of the f_m and f_m' lines in our Fig. 2, Knudsen's[15] data shown in his Fig. 1, page 256 (our Fig. 5), and his Table I, page 258, were used. The μ-values for 55 kc were obtained from his m values and then plotted as a function of h in mole percent. A slight hump was visible near $h=0.1$ percent. This corresponds to a horizontal trace at the 55-kc level in our

[17] K. Schäfer, Zeits. f. physik. Chemie **B46**, 212 (1940).
[18] J. C. Hubbard and I. F. Zartman, Rev. Sci. Inst. **10**, 382 (1939).

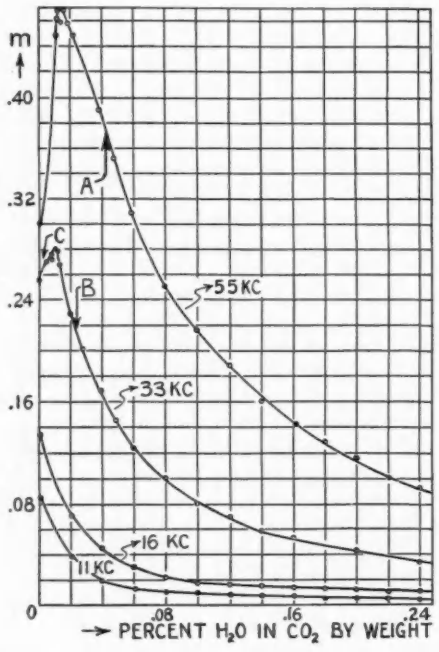


FIG. 5. (Knudsen's and Fricke's Fig. 1. The absorption coefficient m, per cm, of CO_2 containing small amounts of water vapor, for frequencies of 11, 16, 33, and 55 kc.) 0.1 mole percent H_2O at A. Note the slight hump. No hump appears at B but rather at C.

Fig. 2. Then we plotted μ as a function of frequency with $h=0.1$ percent. In this case the hump appeared on the *low* frequency side of the major peak, namely, at about 55 kc. This corresponds to a vertical trace at $h=0.1$ percent in our Fig. 2, and indicates that the f_m and f_m' lines have crossed as shown in our Fig. 2.

Schäfer's[17] statement that *two* β-values can shift the apparent peak position without materially altering its shape substantiates our[8] earlier comments on β-values published by Eucken[3] and van Itterbeek.[7] Some of their peaks seem to be composite ones whose frequency depends on the value of h, the temperature, and the pressure.

Our results for 98°C show that the lines for f_m and f_m' have shifted approximately as shown in Fig. 2 and that the minor peak has become less distinct. We would conclude that the transition probability and the collision efficiency of the CO_2–CO_2 collisions involved in the major peaks have been increased by the temperature rise (see f_m at 28° and 98° for dry CO_2), but that they have been *decreased* for CO_2–H_2O collisions (f_m at 28° and f_m at 98° extrapolated to 100 percent). For the minor peaks they appear to have increased for both types of collision (28° and 98° f' values for $h=0$ and for $h=100$ percent). The value of f' at 98°C and $h=0$ is very uncertain because we have only three rather uncertain points for this curve.

Some of Pumper's[6] observed points (total μ *vs.* $1/p$) for gases with no internal absorption show that the curve should be concave upward. This indicates that his μ_0 (decrement due to scattering) increases with decrease in pressure. Then the curve for μ_0 *vs.* log f/p would swing upward more rapidly. Byers'[19] work with CF_4 at low pressure seems to show such a case. A change in μ_0 near an absorption peak for gases having internal absorption might cause considerable error in the determination of f_m and also of μ_m. This might have a bearing on some of Eucken's β-values mentioned above. The work of Alexander and Lambert[20] with acetaldehyde shows three definite relaxation times. Failure until recently to find definite evidence of more than one in CO_2 and other gases had led to speculation as to possible reasons for a single relaxation time when there are several vibration modes present. The successive f_m values in acetaldehyde differ approximately by a factor of ten. Eucken and Aybar[21] have obtained two absorption peaks with a mixture of COS and CO_2. Their f_m value for pure COS is considerably less than that found by Knudsen.[15, 16]

[19] W. H. Byers, "Supersonic measurements with CF_4," recently submitted for publication in J. Chem. Phys.

[20] E. A. Alexander and J. D. Lambert, Proc. Roy. Soc. **179**, 499 (1942).

[21] A. Eucken and S. Aybar, Zeits. f. physik. Chemie **B46**, 195 (1940).

The Application of Sound Absorption to Factory Noise Problems *

HALE J. SABINE AND R. ALLEN WILSON
The Celotex Corporation, Chicago, Illinois

(Received May 24, 1943)

WHILE the reduction of noise has been successfully achieved during the past years in buildings used for offices, hospitals, schools, and other common gathering places and in a variety of rooms used for many kinds of special purposes, it has remained for the current pressure of wartime demands for manufacturing products to focus any wide-spread attention to the problems found in factory work areas.

Perhaps the greatest single factor in bringing the factory noise problem into the open has been the mass employment of women, which began as a defense and war measure. Here were workers who, not knowing what they were expected to tolerate, were outspoken in their reactions to excessive noise conditions. Here were workers who felt that objectionable noise constituted sufficient reason to change jobs. In some industries, more or less regular absenteeism on the part of women employees led some executives to suspect that noise also had a bearing on this situation.

An interesting case in point is that of a textile mill where, during the past year, women have been brought into the weave sheds. New employees in this plant were given a rather extensive training course. Shortly after taking up the regular work as full time employees, a large percentage of these women left their jobs. By shrewd questioning the superintendent satisfied himself that much of this turnover was due to the reactions to plant noise. Since there is no known method of selecting only those people who can successfully condition themselves to withstand intense noise, he devised the following procedure as a test program. Before entering the training course, new women employees were given small tasks that kept them in or adjacent to the weave sheds. Those who were still on the job at the end of a full week were then entered for the training course. The results of this test were so conclusive and satisfactory that it is now standard practice. It is reported that between 40 and 50 percent of the new women employees undergoing this "trial" period now drop out after the third day and before the week end.

Another example where the problem appeared to be one of nervous fatigue as the result of exposure to noise, rather than difficulty in individual conditioning, was found in a munitions plant manufacturing .30-cal. and .50-cal. machine gun cartridges. Here it was observed that regular women employees were impelled to take brief "vacations" from their jobs at short intervals. Investigation by the plant health directors and engineers convinced them that noise was largely responsible for these absences. They further concluded that these rest periods were essential unless something could be done to modify noise conditions within the departments where these women worked.

There are other instances where noise has been a major factor in excessive turnover in men employees. Early in the growth of the defense program, a west coast factory found that it could not keep men in a department adjacent to a steel chipping operation until measures were taken to protect these men from the noise created by the pneumatic chipping hammers. A mid-west plant making a product vital to all automotive and mechanical equipment experienced the same situation in an automatic machine room.

In response to this increasing interest on the part of industrial hygienists, personnel officers, plant engineers, and others responsible for the efficiency and general welfare of factory workers, the present investigation was undertaken in order to determine what can be done with acoustical treatment to alleviate factory noise conditions.

The initial step in the survey was to determine the range of noise levels encountered in typical factories. Noise level measurements were made in 33 separate plants covering a wide diversity of industries and machine operations. Of all the readings taken in actual work areas, the highest was 130 db and the lowest 65 db. In the large majority of cases, the observed noise levels ranged quite uniformly between approximately

* Paper presented at the twenty-eighth meeting of the Acoustical Society of America, May 14–15, 1943, New York, New York.

85 and 105 db. In order to obtain comparative data on the noise output of various types of machines, readings were taken wherever possible at a fixed distance of 3 feet from the principal noise producing point of the machine. A few representative figures are given in Table I. The data shown should be considered only as illustrative, since in many cases the noise level may vary considerably depending on the type of work or material on which the machine is operating. It should also be noted that since the operator frequently is closer to the noise source than 3 feet, the level at his ear may be somewhat higher than the values shown.

TABLE I. Noise levels of various machines at distance of 3 feet.

Punch presses, various types	96–103
Headers	101–105
Drop hammers	99–101
Bumping hammer	100
Hydraulic press	130
Automatic riveters	95– 99
Lathes (average)	80
Automatic screw machines	93–100
Airplane riveting guns	94–105
Airplane propeller grinding	100–105
Cotton spinning	84– 87
Looms	94–101
Sewing machines	93– 96
Wood planers	98–110
Wood saw	100
Wire rope stranding machines	100–104
Ball mill	99

One of the first questions which arose was whether the reductions in noise level of the order of 5 to 10 decibels theoretically attainable by means of acoustical treatment were enough to afford really worth-while relief when applied to the range of noise levels of approximately 85 to 105 db to which the average factory worker is exposed. Experience with a number of acoustical installations showed that very substantial relief from annoyance was possible even under conditions where noise meter readings showed no significant reduction in noise level. Corollary experiences revealed that it was often possible for an acoustically treated area to be more comfortable from the noise standpoint than an untreated area having actually a lower average noise level. From these observations it was soon concluded that factors other than the noise level contributed important elements to the over-all noise picture.

Analysis of the comments of workers indicated that these factors may be grouped under two headings, namely, reverberation and what may be termed the "spreading effect" of sound. Excessive reverberation seems to evoke a very definite feeling of annoyance apparently arising from the unnatural prolongation of an already disagreeable noise stimulus. Furthermore, the sustaining effect of reverberation on an intermittent or impact type of noise source greatly increases its interference with the understanding of speech, one of the most serious and frequent noise problems in factory areas. It must be noted, however, that when the noise sources are of a steady, continuous type, such as lathes or other rotary machines, the problem of reverberation is not involved and relief from this element of the total noise situation cannot be counted on.

Since reduction of the reverberation time is a primary effect of increasing the absorption in a room, it would be expected, and is borne out by experience, that the most effective use of acoustical treatment in alleviating an over-all noise condition is achieved in those areas where excessive reverberation is most obviously and unmistakably noticeable before treatment. Such areas are generally open, "one-piece" rooms having ceiling heights not less than about one-fifth the smallest floor dimension, and containing noise sources of a diversified and intermittent type at fairly wide spacings. A typical example is an assembly shop manufacturing corrugated metal culverts, housed in a room of 3000 square feet floor area with a 17-foot ceiling. The operations involve corrugating steel sheets, punching rivet holes, forming, riveting, and finally dropping the finished culvert on a concrete floor. It is easy to imagine the effect of an excessively high reverberation time on such noise sources. Analysis of the remarks of the employees and the plant manager after acoustical treatment pointed clearly to the reduction of reverberation as the chief factor in the relief experienced.

By spreading effect is meant the tendency of sound in a non-absorbent room to remain at a fixed level or decrease at a slow rate with increasing distance from the sound source, and the accompanying tendency for large amounts of reflected sound energy to arrive at the listening point from directions other than that of the

sound source. The resulting illusion of distant noise sources being abnormally loud and close at hand, together with the inability to estimate easily the distance and direction of individual noise sources are responsible for the feelings of distraction and general uneasiness experienced by workers under these conditions. The spreading of sound is of course associated with excessive reverberation, although its effects are often audible under conditions where reverberation is not readily noticeable, as in the case of continuous, steady noise sources.

Reduction of this spreading effect is the second important action of acoustical treatment and is usually the most obvious and easily recognized change observed by workers. Typical remarks are "The noise of that machine over there stays where it belongs," or "Before, it seemed like every machine in the plant was making noise, but now I can only hear the ones right around me." Comments of this type incidentally revealed an interesting point, namely, that as far as symptoms of strain and fatigue due to noise are concerned, a machine operator is affected much less by his own machine than by the others in the room in spite of the fact that his own machine, being closest to him, sets up a higher noise level at his ear. This is especially true when the machine is operated by manual control, and also when the noise of neighboring machines is of an intermittent or irregular type, as from a battery of punch presses. The explanation probably lies simply in the fact that by directing attention to and controlling his own machine, the operator has a chance to "brace himself" against its noise. At any rate, it is undoubtedly this relative immunity of the average operator to annoyance caused by his own machine that makes possible the increase in working comfort actually realized through reduction of the spreading effect.

The amount of relief obtainable by cutting down the spread of noise is influenced greatly by the spacing and layout of the machines in a given area and by the type of noise they produce. The manner in which these factors affect the final result can be understood by considering the spreading effect in somewhat greater detail. It is well known that the introduction of absorbing material in a room reduces the intensity of distant noise sources more than the intensity of sources close to the point of observation. In order for absorption to be effective at any given position, as far as the ear is concerned, conditions must be such that before treatment the noise of distant sources is audible in the presence of nearby sources. In other words, no good will result from quieting distant sources if their noise is already completely masked by the noise from those in the immediate vicinity. This means that wide spacing of machines, differing qualities of noise from various units, and intermittent operation of the machines, are all conditions favorable to the attainment of good results. For example, treatment applied over punch press areas in which the machines are spaced at least 5 or 6 feet apart has proved a distinct benefit to the operators.

Situations where a number of continuously operating machines having identical noise characteristics are spaced very closely together afford negligible possibility of relief by the use of absorption for workers in the midst of the machines. If, however, only a part of the room is occupied by these machines and absorbing material is applied over the entire room, those workers regularly occupying the portion away from the machines will receive the full benefit of the treatment in cutting down the spread of noise into their area, and will experience the feeling of the noise being "pushed back" to where it belongs. The operators of the machines observe an immediate and pronounced drop-off in the noise in moving only a few steps from the edge of the machine area, and insofar as their duties permit they are afforded periods of relief from time to time which experience has shown to be very much worth while.

The increased facility in locating individual noise sources resulting from the reduction of the spreading effect of sound is a distinct advantage in the frequent cases where the operation of machines is gauged by ear. For example, the superintendent of a factory manufacturing wire cable reported that defective stranding by a machine is usually preceded by a warning "squeal." Before installation of acoustical treatment, time was consumed in determining which of the many machines in the room was at fault, but now, he says, he can "walk right to it."

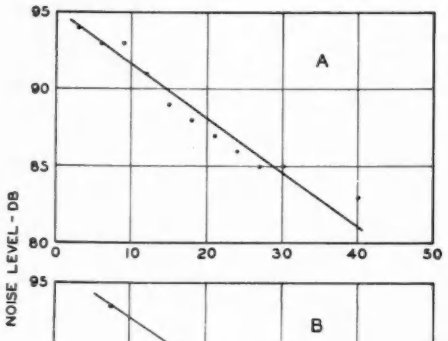


FIG. 1. Attenuation of noise level with distance from the source in large rooms with highly absorbent ceilings. (A) Room dimensions 100′×100′×9′. Slope of line, 0.35 db per foot. (B) Room dimensions 360′×560′×27′. Slope of line, 0.16 db per foot.

One important phase of the investigation was to establish, if possible, a theoretical basis on which to interpret and predict results from the use of absorption in industrial areas. The conventional method of calculating the noise reduction in decibels, arrived at by assuming that the average sound intensity in a room is inversely proportional to the total number of absorption units, has the advantage of simplicity, but usually has little or no physical significance when applied to actual conditions in factories, particularly in the case of very large areas. In the first place, the decibel reductions predicted by the theory refer only to the level of the generally reflected sound, and can, therefore, be realized only at points far enough away from the nearest noise source that the relative level of the direct sound is negligible. Since this distance is usually much greater than the normal spacing of machines, the calculated reductions cannot be expected under operating conditions inside of machine areas. In the second place, actual measurements made under conditions where the noise level due to a single source could be observed over a wide range of distances show that in rooms with highly absorbent ceiling treatment the intensity instead of levelling off to a constant value at the distance from the source predicted by the theory continues to decrease at more or less a constant rate clear to the limits of the room. This means that the actual decibel reduction due to the addition of treatment instead of being a fixed quantity at all points beyond a certain distance, is continuously variable with distance, and that in predicting or specifying a decibel reduction, a corresponding distance must be specified.

These considerations, together with the fact indicated by experience that it is the reduction of the spreading effect of noise rather than reduction of noise level *per se* that is responsible for the results achieved by acoustical treatment, suggest that the effectiveness of a given acoustical installation may better be expressed in terms of the *attenuation of noise level with respect to distance from the source.* The higher this attenuation figure, the greater the reduction of noise from distant sources in relation to that from nearby sources, or, in other words, the greater the reduction in spreading.

While it has not been possible to carry out a study of attenuation characteristics detailed enough to afford a method of predicting results by calculation, nevertheless a number of useful observations of a general nature have been made:

(1) In rooms whose smallest floor dimension is at least several times the ceiling height, and having a highly sound absorbent ceiling, the intensity level due to a single source or concentration of sources decreases at a constant rate in decibels per foot over the entire area of the room, regardless of its size.

(2) This constant rate of attenuation varies inversely with the ceiling height. Attenuations of the order of 0.4 db per foot have been measured

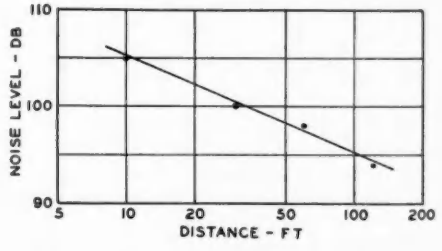


FIG. 2. Attenuation of noise level with distance from the source in a large room with untreated ceiling. Room dimensions 170′×200′×26′. Slope of line, 3 db per distance double.

for ceiling heights averaging 10 feet, and 0.2 db per foot for ceiling heights in the 20-foot range, the ceiling materials having absorption coefficients of at least 0.70. (See Fig. 1.)

(3) These attenuation rates are established at a distance from the source somewhat less than the ceiling height. Within this distance the intensity rises much more rapidly at a rate determined partly by the inverse square law and partly by the distribution of the noise source elements.

(4) The attenuation in the case of untreated ceilings is not only much smaller, but has a different characteristic, being of the order of 3 db per distance double. (See Fig. 2.)

All of these observations, and the latter in particular, suggest that in a large, low-ceilinged room, sound energy instead of being in a diffuse condition is contained largely in cylindrical waves which in travelling outward from the source are attenuated both by distance and by the absorption of the ceiling. The process, in fact, may be considered as analogous to attenuation in an absorbent-lined duct except that transmission takes place radially over a plane instead of in a single line.[1]

In cases where greater attenuation is needed than can be obtained by lowering the ceiling and increasing the absorption coefficient of the ceiling material, the use of baffles of absorbing material suspended from the ceiling is indicated. Although sufficient data have not been collected to permit exact design specifications for optimum performance, it would be expected that the closer the baffles are spaced and the lower the level to which they extend, the more effective will be the results.

[1] Cf. G. E. Morison, J. Acous. Soc. Am. 9, 244 (1938).

An Improved Telephone Receiver Analysis

R. D. FAY
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received March 15, 1943)

The method of determining the performance of electromagnetic telephone receivers from input measurements has been extended and improved. It is shown that not only may an actual receiver at any one frequency be correctly represented by a simple piston-phone but also the the position of the equivalent piston may be chosen arbitrarily, say at the mouth of the receiver. The characteristics of the equivalent piston-phone for all positions of the piston are easily found graphically from a single, simple diagram constructed from data which are readily obtained from a few input measurements. The accuracy of the method has been tested experimentally by making independent measurements at the output end of the receiver. The results check closely.

INTRODUCTION

IN a previous paper,[1] it is shown how the parameters which determine the performance of an electromagnetic telephone receiver may be determined from measurements of input impedance taken as a function of the length of closed air column into which the receiver works. Insofar as the plug which terminates the air column is a perfect reflector and the losses in the air column are negligible, this scheme furnishes a convenient means for obtaining all possible values of reactive air load. The locus of input impedance plotted as a plane vector is proved to be a circle for such air loads. A graphical construction based on this circle may be used to advantage to determine the required parameters.

The method has been found distinctly useful. Very little special apparatus is required and the precision in most cases is satisfactory. There are, however, undesirable features in the method, especially those which arise from having an equivalent piston in a fixed position which is usually inaccessible. In finding the air load at the mouth of the receiver, for example, three steps are required: to find the effective distance between the piston face and the mouth; to find the air load on the piston; and to find from these data the air load at the mouth. A more serious objection is the difficulty in finding the exact position of the plunger which terminates the closed air column in order that the motion of the piston is effectively blocked. Even for the relatively simple case of the moving-coil mechanism this determination requires undue time and care, and for the moving-iron type of receiver no entirely satisfactory blocking means are known.

[1] R. D. Fay and W. M. Hall, J. Acous. Soc. Am. **5**, 46 (1933).

THE NEW METHOD

In the improved method, these disadvantages are entirely eliminated. The acoustical quantities are found directly at the mouth of the receiver or at any other reference plane in the air column. Fewer measurements are required, the data are obtained more easily, and the graphical construction is very considerably simplified.

The improvements and simplifications have been effected largely by adopting a new point of view in the analysis. The receiver is treated as a linear four-terminal network wherein the acoustical system is implicitly handled as an equivalent electrical system. The analysis is restricted to electroacoustical transducers comprising electromagnetic coupling between the systems. In this type of coupling the mechanism is such that at the coupling point an electromotive force is generated proportional to the velocity and a mechanical force is generated proportional to the current. Hence a mechanical impedance appears as an electrical admittance. In particular an infinite mechanical impedance is equivalent to

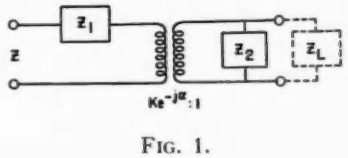


FIG. 1.

an electrical short circuit and a zero mechanical impedance is equivalent to an electrical open circuit.

It is known that the behavior of a four-terminal linear network at a single frequency is completely determined by three complex parameters. These may conveniently be expressed as any three of the four open- and short-circuit impedances. It follows that any two networks which have the same open- and short-circuit impedances at a given frequency will be equivalent at that frequency. The network shown in Fig. 1 comprises three parameters in convenient relationships. For the present analysis, however, the transformer indicated in the network must have a complex turns ratio.

The parameters of this network are Z_1, Z_2, and $Ke^{-j\alpha}$. The impedance, Z, looking into the network when a load impedance, Z_L, is connected across the output terminals is given by

$$Z=Z_1+\frac{K^2e^{-2j\alpha}}{(1/Z_2)+(1/Z_L)}.$$

In particular, if $Z_L=0$, the resulting short-circuit input impedance is Z_1. If $Z_L=\infty$, the resulting open-circuit input impedance is

$$Z_1+\frac{K^2e^{-2j\alpha}}{(1/Z_2)}.$$

If the input terminals are open, the open-circuit impedance looking back from the output terminals is Z_2.

For a network with an electrical input and a mechanical output where the coupling is electromagnetic, the electrical impedances Z_2 and Z_L will represent mechanical admittances. In particular, $1/Z_2$ is the mechanical impedance of an equivalent piston, that is to say, it is the actual mechanical impedance seen looking back into the device when there is no contribution from the electrical system. This impedance is called Z_P. In like manner, $1/Z_L$ is the mechanical impedance of the load into which the device works. In a telephone receiver the load is an air load and is here called Z_A.

The electrical impedance, Z_1, is then the terminal impedance seen when the piston is blocked, that is, when Z_A is infinite, corresponding to $Z_L=0$. Following the usual nomenclature this is called the blocked impedance and is designated by Z_{EB}. Note, however, that the blocked impedance as here defined is the input impedance measured when an equivalent piston is blocked; the actual diaphragm is in general free to move. The flexibility resulting from this point of view in regard to blocked impedance is chiefly responsible for the simplification in the analysis. Finally, the input impedance is designated by Z_{ET}. Then the expression for input impedance as a function of air load impedance becomes

$$Z_{ET}=Z_{EB}+\frac{K^2e^{-2j\alpha}}{Z_P+Z_A}.$$

This expression is identical in form to that developed in connection with the former method. Network theory, however, shows that this relation is valid when the mechanical system comprises any linear acoustical network in addition to the diaphragm assembly.

Following the conventional terminology, the motional impedance Z_{MOT} is defined as the difference between the blocked and the free impedance or

$$Z_{MOT}=\frac{K^2e^{-2j\alpha}}{Z_P+Z_A}.$$

The total mechanical impedance, Z_M, is the sum of Z_P and Z_A

MOTIONAL AND LOAD IMPEDANCE

One of the most important relationships in the analysis is the fact that the power transmitted by the electrical system must equal the power received by the mechanical system. Letting I represent the r.m.s. value of the current driving the equivalent piston and V represent the r.m.s. value of the velocity of the equivalent piston, the average power received by the piston is V^2R_M. The average power transmitted electrically is the product of I^2 and the real part of $Z_{MOT}e^{+2j\alpha}$. To simplify this expression, another impedance called the electrical load impedance, Z_{EL}, is introduced.

By definition, $Z_{EL}=Z_{MOT}e^{2j\alpha}$, hence $V^2R_M=I^2R_{EL}$ expressed in consistent units.

It is also seen that $Z_{EL}=K^2/Z_M$, where K is real.

The electrical load impedance then is equal in magnitude to the motional impedance and has the same phase angle as the reciprocal (hence the conjugate) of the mechanical impedance.

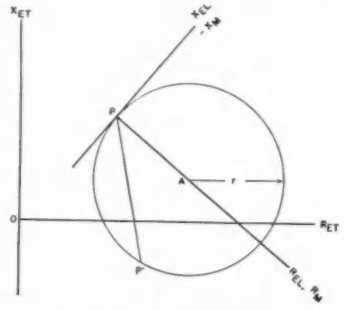


FIG. 2. The basic circle.

The fundamental relations between impedances may be summarized as follows:

$$Z_{ET}=Z_{EB}+Z_{EL}e^{-2j\alpha},$$

$$Z_{EL}=\frac{K^2}{Z_M},$$

$$Z_M=Z_P+Z_A.$$

In the graphical method to be described, the parameters are determined from a circle diagram the data for which is obtained from measurements of the input impedance, Z_{ET}, as a function of reactive air loads of known value. Known reactive air loads of any magnitude are readily obtained by working the device into a tube of air terminated by a sliding plug. Ideally, the impedance of the air column contained in a rigid tube terminated in a perfect reflector is

$$Z_A=-jZ_0\cot\frac{2\pi l}{\lambda},$$

where

l is the length of the air column,
λ is the wave-length,
Z_0 is the surge impedance given by
$Z_0=\rho ca$,

where

ρ is the density of air,
c is the velocity of sound propagation,
and a is the cross-sectional area of the tube.

THE CIRCLE DIAGRAM

The plane vector representing Z_{EL} corresponding to reactive values of Z_A will terminate on a circle. Thus:

$$R_{EL}+jX_{EL}=\frac{K^2}{R_P+j(X_P+X_A)},$$

where R_P is constant.

Solving for R_P,

$$R_P=\frac{K^2R_{EL}}{R_{EL}^2+X_{EL}^2},$$

$$\left(R_{EL}-\frac{K^2}{2R_P}\right)^2+X_{EL}^2=\left(\frac{K^2}{2R_P}\right)^2.$$

On Z_{EL} coordinates, this represents a circle, of radius $r=K^2/2R_P$, tangent to the X_{EL} axis at the origin.

In order to have correct vectorial addition the Z_{EL} axes are rotated through the angle -2α with respect to the axes of Z_{ET} as shown in Fig. 2. In the diagram, O is the origin of the Z_{ET} coordinates; OP represents the blocked impedance, Z_{EB}; hence P is the origin of the Z_{EL} coordinates. Furthermore, the radius, PA, coincides with the R_{EL} axis so that the angle 2α is the angle, measured clockwise, that PA makes with R_{ET}.

The circle of Fig. 2 is the basis of all subsequent analysis and is therefore called the basic circle.

The value of Z_{ET} corresponding to zero air load is OP'. Therefore, PP' represents the impedance $Z_{EL}=K^2/Z_P$. The axes of Z_M must coincide with those for Z_{EL}, but if the X_M axis is reversed, corresponding values for electrical load impedance and mechanical impedance will be represented by vectors which coincide in direction. Using this scheme, the piston impedance vector, Z_P, must lie in the chord PP'. It remains only to determine the magnitude of Z_P in terms of the calculated surge impedance, Z_0.

"QUARTER-WAVE CHORDS"

A newly found relationship makes possible the determination of the ratio Z_P/Z_0 in a manner which avoids the confusion inherent in the previous method.

Note that the terminal impedances OP and OP' are measured with the device working into air columns whose lengths differ by one-quarter wave-length, and that these two measurements determine the chord PP'. It will be proved that all other chords determined from measurements made with a quarter-wave-length interval in air column loading intersect the PP' chord in a common point, called C. It will further be proved that the vector PC represents the piston impedance, Z_P, if a scale for mechanical impedances is chosen such that

$$|Z_0|^2 = r^2 - \langle AC \rangle^2,$$

where A is the center of the basic circle. Actually, a complete analysis of the device at the chosen frequency is possible when the points P, A, and C are determined on the Z_{ET} coordinates.

The proof concerning the intersection of chords is simplified by considering the receiver to comprise a length of the air loading column just sufficient to make the piston impedance a pure resistance, R. It is obvious that a proof made on this basis is quite general since it is only the difference in air column lengths that are specified. The proof is made with reference to Fig. 3.

Let

$$2\pi l/\lambda = \phi.$$

Then

$$Z_A = -jZ_0 \cot \phi, \quad \text{and} \quad Z_{EL} = \frac{K_0^2}{R - jZ_0 \cot \phi}.$$

Increments in the air column length, l, of a quarter-wave-length correspond to increments in ϕ of 90°. When $\phi = 0$, the blocked impedance is represented by OP_0, that is P_0 is the origin for the Z_{EL} coordinates. When $\phi = 90°$, $Z_{EL} = P_0P_0' = K_0^2/R = 2r$, which is the diameter of the basic circle. The chord perpendicular to this diameter is determined from measurements made with $\phi = \pm 45°$. For these values, $Z_{EL} = P_0N$ and P_0N'. Let the intersection of the diameter P_0P_0' and the chord NN' be called C. Then P_0C, the real part of P_0N is

$$\frac{K_0^2 R}{R^2 + Z_0^2} \text{ in electrical ohms.}$$

Let P_0T represent Z_{EL1} corresponding to $\phi = \phi_1$ and let P_0T' represent Z_{EL2} for $\phi = \phi_1 + 90°$.

The angle TCP_0' is then

$$\tan^{-1} \frac{X_{EL1}}{R_{EL1} - P_0C},$$

and the angle $T'CP_0$ is

$$\tan^{-1} \frac{X_{EL2}}{R_{EL2} - P_0C}.$$

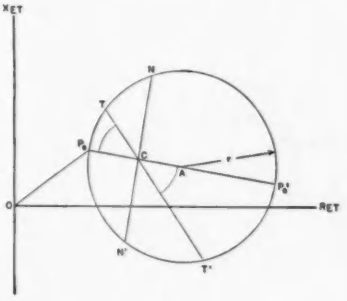


FIG. 3.

Therefore

$$\tan TCP_0' = \frac{X_{EL1}}{R_{EL1} - P_0C}$$

$$= \frac{K_0^2 Z_0 \cot \phi_1}{K_0^2 R - \left(\frac{K_0^2 R}{R^2 + Z_0^2}\right)(R^2 + Z_0^2 \cot^2 \phi_1)}$$

$$= \frac{Z_0(R^2 + Z_0^2) \cot \phi_1}{R[R^2 + Z_0^2 - R^2 - Z_0^2 \cot^2 \phi_1]}$$

$$= \frac{(R^2 + Z_0^2) \cot \phi_1}{RZ_0(1 - \cot^2 \phi_1)}.$$

Also, since

$$\cot (\phi_1 + 90°) = -\frac{1}{\cot \phi_1}$$

$$\tan T'CP_0 = \frac{X_{EL2}}{R_{EL2} - P_0C}$$

$$= \frac{-K_0^2 Z_0 / \cot \phi_1}{K_0^2 R - \left(\frac{K_0^2 R}{R^2 + Z_0^2}\right)\left(R^2 + \frac{Z_0^2}{\cot^2 \phi_1}\right)}$$

$$= \frac{-Z_0(R^2 + Z_0^2) \cot \phi_1}{R[(R^2 + Z_0^2 - R^2) \cot^2 \phi_1 - Z_0^2]}$$

$$= \frac{(R^2 + Z_0^2) \cot \phi_1}{RZ_0(1 - \cot^2 \phi_1)}.$$

Since the angles equal each other for all values of ϕ_1, all chords so determined intersect in the point C.

For the particular case when $\phi=45°$,

$$(r^2-\langle AC\rangle^2)^{\frac{1}{2}}=CN$$

and

$$\frac{CN}{P_0C}=\frac{X_{EL}}{R_{EL}}=\frac{Z_0}{R}.$$

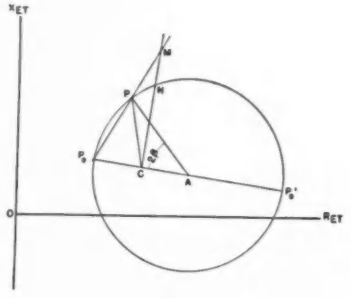


FIG. 4.

Hence if the scale for mechanical impedance is such that $(r^2-\langle AC\rangle^2)^{\frac{1}{2}}$ represents the magnitude of Z_0, P_0C represents Z_P, which in this case is R.

It remains to show that if this same scale is chosen for mechanical impedance for the receiver without the added air column the piston impedance Z_P will be represented by PC when OP is the blocked impedance.

Since Z_P is the impedance seen looking back into the receiver (with the electrical terminals open) we can readily calculate the impedance with an added air column in terms of the unloaded value. Thus:

$$Z=Z_0\tanh(\psi+j\phi).$$

When $\phi=0$,

$$Z=R=Z_0\tanh\psi.$$

Actually, a length of air column equivalent to a change in ϕ of ϕ_0 was added. Therefore:

$$Z_P=Z_0\tanh(\psi-j\phi_0).$$

It will be sufficient to show that $|Z_P|$ is represented by PC when $r^2-\langle AC\rangle^2$ represents Z_0^2.

In Fig. 4, which represents the same circle as does Fig. 3, M is the intersection of P_0P produced and of CN produced.

The electrical impedance P_0P then corresponds to the mechanical impedance P_0M, where

$$P_0M=R-jZ_0\cot\phi_0=P_0C+jCM.$$

Let $\angle PAP_0=-2\beta$,

$$\frac{CM}{CP_0}=-\frac{Z_0\cot\phi_0}{R}=-\frac{r\sin 2\beta}{r(1-\cos 2\beta)}=-\cot\beta.$$

Then

$$\tan\phi_0=\frac{Z_0}{R}\tan\beta, \quad \text{and} \quad \tanh\psi=\frac{R}{Z_0}.$$

But

$$Z_P=Z_0\frac{\tanh\psi-j\tan\phi_0}{1-j\tanh\psi\tan\phi_0}=\frac{R-j\dfrac{Z_0^2}{R}\tan\beta}{1-j\tan\beta},$$

or

$$|Z_P|^2=\frac{R^2+\dfrac{Z_0^4}{R^2}\tan^2\beta}{(1+\tan^2\beta)}=R^2\cos^2\beta+\frac{Z_0^4}{R^2}\sin^2\beta.$$

But if CN represents Z_0 and P_0C represents R,

$$\frac{Z_0^2}{R}=(2r-R).$$

Hence $|Z_P|^2=R^2+4r(r-R)\sin^2\beta$.

It will now be shown that $|PC|^2$ has this same value. From the triangle PCA, where $AC=r-P_0C=r-R$,

$$\begin{aligned}|PC|^2&=r^2+\langle AC\rangle^2-2r\langle AC\rangle\cos 2\beta,\\&=r^2+(r-R)^2-2r(r-R)\cos 2\beta,\\&=R^2+2r(r-R)(1-\cos 2\beta),\\&=R^2+4r(r-R)\sin^2\beta,\\&=|Z_P|^2 \quad \text{Q.E.D.}\end{aligned}$$

TABLE I.

Reading No.	Letter	Tube length cm	Resistance R_{ET} ohms	Reactance X_{ET} ohms	Remarks
1		37.00	14.5	1.7	$\Delta l=21.64=\lambda/2$
2		15.36	14.4	1.7	$\Delta l=10.82=\lambda/4$
6		4.54	45.7	9.5	
3		16.82	14.5	3.3	$\Delta l=\lambda/4$
5		6.00	36.2	−15.0	
4	P'	10.82	15.5	− 4.5	$\Delta l=\lambda/4$
7	P	0.00	16.4	9.8	

EXAMPLE

A numerical example will serve to illustrate how the method works.

The half-wave-length is determined by finding the difference in tube length required to close the circle. Since attenuation in the tube is not exactly zero, points at half-wave intervals will not coincide exactly, but if the initial point is chosen to give approximately a minimum resistance reading, a change in tube length may be found such that the initial reactance reading is exactly duplicated, disregarding a small change in resistance. This procedure has been found entirely practical. In the example, tube lengths are measured from the mouth of the receiver which is taken as the reference plane.

Table I shows a set of readings, and the order in which they were taken. The frequency was about 795 c.p.s., giving $2\pi f = 5000$.

It should be noted that the tube used in obtaining these data was packed in sand. Without some such precaution the system tends to lack stability manifested by fluctuations in the bridge balance.

These points are plotted in Fig. 5. A circle is drawn which passes within $\frac{1}{4}$ ohm of each point; the true points are assumed to lie exactly on the circle. The quarter-wave chords are also drawn.

APPLICATIONS

With the basic circle, the blocked impedance, and the intersection point, C, determined, the entire performance of the device for any load condition may be found from input measurements and measurements of lengths on the circle diagram (without further graphical construction). Figure 5 shows the basic circle. The symbols have the same meaning as heretofore. The input impedance is represented by OT.

The expression for efficiency is found as follows:

Let I be the r.m.s. value of the current at the terminals and let V be the r.m.s. value of the velocity of the equivalent piston. The average power input is then I^2R_{ET}, the average output is V^2R_A, the average power transmitted to the mechanical system is I^2R_{EL} which must equal V^2R_M in consistent units.

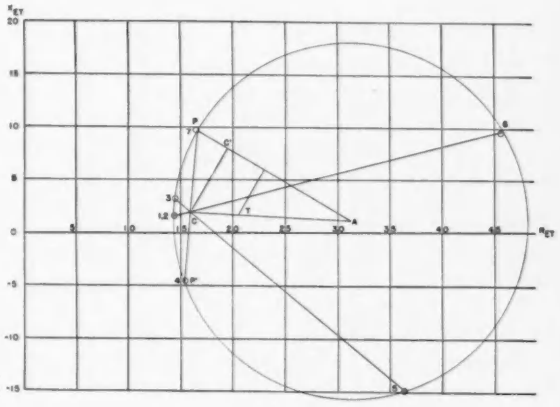


FIG. 5.

Then the efficiency is given by

$$\eta = \frac{\text{output}}{\text{input}} = \frac{V^2R_A}{V^2R_M} \cdot \frac{I^2R_{EL}}{I^2R_{ET}} = \frac{R_A}{R_M} \cdot \frac{R_{EL}}{R_{ET}}.$$

But

$$\frac{R_{EL}}{R_M} = \left|\frac{Z_{EL}}{Z_M}\right| = \frac{|Z_{EL}|^2}{K^2}.$$

Also,

$$R_A = R_M - R_P,$$

but

$$R_M = R_{EL}\frac{K^2}{Z_{EL}{}^2}, \quad \text{and} \quad R_P = \frac{K^2}{2r}.$$

Therefore

$$R_A = \frac{K^2}{Z_{EL}{}^2}\left(\frac{2r \cdot R_{EL} - Z_{EL}{}^2}{2r}\right)$$

therefore

$$\frac{R_AR_{EL}}{R_M} = \frac{2r \cdot R_{EL} - Z_{EL}{}^2}{2r}.$$

But

$$Z_{EL}{}^2 = R_{EL}{}^2 + X_{EL}{}^2;$$

therefore

$$2r \times R_{EL} - Z_{EL}{}^2 = r^2 - [X_{EL}{}^2 + (r - R_{EL})^2].$$

Referring now to Fig. 5:

R_{EL} is the projection of PT on the radius PA,

and

X_{EL} is the perpendicular component of PT.

Hence

$$X_{EL}{}^2 + (r - R_{EL})^2 = \langle AT \rangle^2$$

and

$$\eta = \frac{r^2 - \langle AT \rangle^2}{2r \cdot R_{ET}}.$$

The efficiency of the device may therefore be found without knowing the blocked impedance

and without an explicit evaluation of any mechanical impedance.

It is of interest to find the maximum efficiency which can be obtained from a given receiver. Obviously, the maximum must occur when T lies on the diameter parallel to the R_{ET} axis. For this case, let $AT=x$. Also, let the maximum and minimum values for R_{ET} on this diameter be R_2 and R_1, respectively.

Then

$$\eta=\frac{\left(\frac{R_2-R_1}{2}\right)^2-x^2}{(R_2-R_1)\left(\frac{R_1+R_2}{2}+x\right)}.$$

Setting $d\eta/dx=0$, gives $x=-\frac{1}{2}[(R_2)^{\frac{1}{2}}-(R_1)^{\frac{1}{2}}]^2$. Substituting,

$$\text{maximum efficiency is } \frac{(R_2/R_1)^{\frac{1}{2}}-1}{(R_2/R_1)^{\frac{1}{2}}+1}.$$

The value of R_{ET} for which the maximum efficiency occurs is, of course,

$$\frac{R_1+R_2}{2}+x=(R_1R_2)^{\frac{1}{2}};$$

and X_{ET} is the reactive component of the center of the circle.

Having determined the efficiency, it is a simple matter to determine the acoustical output in terms of the voltage, E, at the input.

Since the input is $\frac{E^2R_{ET}}{|Z_{ET}|^2}$, the output is

$$\frac{\eta R_{ET}}{|Z_{ET}|^2}\cdot E^2,$$

or

$$\text{output}=\frac{r^2-\langle AT\rangle^2}{2r|Z_{ET}|^2}\cdot E^2.$$

If practical electrical units are used, the output will be in watts.

AIR LOAD IMPEDANCE

In the determination of the air load impedance, Z_A, and also the sound pressure at the output, it is necessary to evaluate the factor K^2. The fundamental expression for this factor determined from the circuit diagram shown in Fig. 1 is the difference between the open- and short-circuit input impedances divided by the open-circuit admittance measured at the output terminals. The magnitude of the ratio determines K^2. Since the difference between the open- and short-circuit impedances is represented by the vector PP' of Fig. 5 and the open-circuit admittance corresponds to the mechanical impedance Z_P, $K^2=|PP'|\,|Z_P|$.

It has been shown that $\frac{Z_P}{Z_0}=\frac{PC}{(r^2-\langle AC\rangle^2)^{\frac{1}{2}}}$.

For purposes of calculation, it is simpler to express this ratio in another form. In Fig. 5, consider the similar triangles inscribed in the basic circle determined by the chord PP' and the diameter through the point C.

$$\frac{PC}{r+AC}=\frac{r-AC}{P'C}.$$

Hence

$$\frac{PC}{(r^2-\langle AC\rangle^2)^{\frac{1}{2}}}=\left(\frac{PC}{P'C}\right)^{\frac{1}{2}}, \quad \text{and} \quad Z_P=Z_0\left(\frac{PC}{P'C}\right)^{\frac{1}{2}}.$$

Therefore

$$K^2=Z_0\cdot PP'(PC/P'C)^{\frac{1}{2}},$$

where only magnitudes are considered.

It will be seen that only two magnitudes need be scaled in this expression and that no additional graphical construction is required.

To avoid the measurement of angles in the evaluation of the air load impedance, $|Z_A|$ and R_A may be found separately as follows.

$$Z_A=Z_M-Z_P.$$

$$Z_M=\frac{K^2}{Z_{EL}}=\frac{K^2}{PT}, \quad \text{and} \quad Z_P=\frac{K^2}{PP'}.$$

Hence,

$$Z_A=K^2\left(\frac{1}{PT}-\frac{1}{PP'}\right)$$

or

$$|Z_A|=\frac{K^2}{|PP'|}\left|\frac{P'T}{PT}\right|=|Z_P|\left|\frac{P'T}{PT}\right|.$$

Therefore,

$$|Z_A|=Z_0\left(\frac{PC}{P'C}\right)^{\frac{1}{2}}\cdot\left|\frac{P'T}{PT}\right|.$$

To find R_A, it is convenient to start from the expression for efficiency already developed.

$$R_A=\frac{R_M}{R_{EL}}\left(\frac{r^2-\langle AT\rangle^2}{2r}\right)=\frac{K^2}{\langle PT\rangle^2}\left(\frac{r^2-\langle AT\rangle^2}{2r}\right).$$

Putting in the value for K^2 gives

$$R_A=\left(\frac{r^2-\langle AT\rangle^2}{2r}\right)\cdot\frac{PP'}{\langle PT\rangle^2}\left(\frac{PC}{P'C}\right)^{\frac{1}{2}}\cdot Z_0.$$

PRESSURE-VOLTAGE RELATIONS

In determining the magnitude of the acoustic pressure at the output plane in terms of the voltage on the input terminals, it is necessary to pay careful attention to the system of units which is used.* If practical electrical units and c.g.s. mechanical units are used, the energy transmitted from the electrical system to the mechanical system is

$$I^2R_{EL}=V^2R_M\times10^{-7}\text{ watt.}$$

In the relations that follow, only the magnitudes of the vectors are considered.

$$IZ_{ET}=E\text{ volts}\quad\text{and}\quad VZ_A=pa\text{ dynes,}$$

where p is the r.m.s. value of the sound pressure.

$$\text{Since }\frac{R_{EL}}{R_M}=\frac{Z_{EL}^2}{K^2}$$

$$\frac{pa}{E}=\frac{Z_A}{Z_{ET}}\cdot\frac{Z_{EL}}{K}\cdot10^{7/2}\text{ dynes per volt.}$$

Substituting relations already found

$$\frac{pa}{E}=\left[\frac{10^7Z_0}{PP'}\left(\frac{PC}{P'C}\right)^{\frac{1}{2}}\right]^{\frac{1}{2}}\cdot\frac{P'T}{OT}\text{ dynes per volt.}$$

For ordinary conditions where

$$Z_0=41.6a\ \frac{\text{dynes}}{\text{cm per sec.}}$$

$$\frac{p}{E}=\left[\frac{41.6\times10^7}{aPP'}\left(\frac{PC}{P'C}\right)^{\frac{1}{2}}\right]^{\frac{1}{2}}\frac{P'T}{OT}$$

dynes per sq. cm per volt.

* In the previous paper, failure to pay sufficient attention to units led to a grotesque numerical error.

Note that the area a is the area of the calibrating air column in sq. cm and PP' is in electrical ohms.

It is of interest to note how simple this expression becomes in terms of K. Without putting in the steps the original expression reduces to

$$\frac{pa}{E}=\frac{K}{OT}\left(1-\frac{PT}{PP'}\right).$$

If the output is blocked, $PT=0$ and $pa=K(E/OT)=KI$.

It will be noted that it has been implicitly assumed that there is substantially plane-wave motion in the calibrating air column and any air passages in the unit. In effect, this criterion is met if the diameter of any air passage is small with respect to the wave-length. However, consistent results have been obtained where the diameter of the air column was nearly large enough to permit a transverse mode of vibration.

A few numerical examples will serve to illustrate some of the applications of the method.

The points which are used in obtaining the numerical results are shown on Fig. 5. The terminal impedance, OT, is that which would be obtained for an air load $Z_A=Z_0(1+j0)$ which is considered to be a standard load.

The numerical data required are listed. The lengths are given in ohms. Radius of circle, $r=16.8$

$PC=7.65$ $\quad P'C=6.65$
$PP'=14.30$
$AT=10.6$ $\quad\therefore r^2-\langle AT\rangle^2=170.$ $\quad P'T=8.2$
$OT=20.6$ $\quad R_{ET}=20.5$
$a=2.80$ sq. cm, $\quad\rho c=41.6$ dynes/cm$^2\div$cm/sec.,
$\therefore Z_0=116$ mech. ohms.

First, the value of Z_P/Z_0 obtained from the circle diagram will be compared with that obtained by direct measurement using an acoustic line.*

The radial and tangential projections of PC, PC' and $C'C$, are 3.40 and 6.85 ohms, respectively.

Hence from the diagram,

$$\frac{R_P+jX_P}{Z_0}=\frac{3.40+j6.85}{7.25}=0.469+j0.945.$$

* W. M. Hall, J. Acous. Soc. Am. **11**, 1 (1939).

The value measured by the acoustic line is $0.475+j0.920$. The agreement is considered entirely satisfactory.

A number of measurements of this kind, many of them made as assigned laboratory experiments have yielded values which differ on the average by about 3 percent.

The efficiency is found from the expression:

$$\eta=\frac{r^2-\langle AT\rangle^2}{2r\cdot R_{ET}}=\frac{170}{2\times16.8\times20.5}=24.6 \text{ percent.}$$

The maximum possible efficiency is

$$\frac{(R_2/R_1)^{\frac{1}{2}}-1}{(R_2/R_1)^{\frac{1}{2}}+1}.$$

Since $R_2=47.9$ and $R_1=12.3$, $(R_2/R_1)^{\frac{1}{2}}=1.97$.

Hence maximum efficiency is $97/297=32.6$ percent.

Finally, substituting in the expression

$$\frac{p}{E}=\left[\frac{4.16\times10^8}{a\times PP'}\left(\frac{PC}{P'C}\right)^{\frac{1}{2}}\right]^{\frac{1}{2}}\frac{P'T}{OT},$$

$$\frac{p}{E}=\left[\frac{4.16\times10^8}{2.80\times14.3}\left(\frac{7.65}{6.65}\right)^{\frac{1}{2}}\right]^{\frac{1}{2}}\cdot\frac{8.2}{20.6}$$

$=1330$ dynes per sq. cm per volt.

CONCLUSION

The method which has been described has been found especially useful in connection with the absolute calibration of microphones at specific frequencies in that a sound pressure in a specified plane may be calculated with a probable error which can readily be estimated. Under favorable conditions, the error in the determination should not exceed $\frac{1}{2}$ percent, assuming that the calculated value of the characteristic impedance, Z_0, is correct. If the impedance measurements for closed air column loads determine points which fall on a circle within the precision of measurements, and if the quarter-wave chords intersect precisely in a point, it is reasonable to suppose that the measurements are reliable. It is, however, essential to make sure that the plunger which terminates the air column is substantially an infinite impedance. If there is energy absorbed at the termination, a circle with a common intersection of chords will be determined, but this will not be the basic circle as defined above. If the termination is a pure reactance with a finite value, the basic circle will be determined but the blocked impedance, OP, will be in error as the point P will be incorrectly located.

A brass or an iron plunger three or four diameters in length has been found to constitute an adequate termination for an air column contained in a tube provided the tube is damped by sand or other means to prevent longitudinal vibrations. For loud-speaking telephone receivers in which the sound-radiating surface has a diameter of eight inches or more, an air column in a heavy vertical pipe terminated by water has proved to be satisfactory.

In conclusion, it may be pointed out that when the terminal impedance is plotted as OT, the locus of T is a circle not only when R_A is constant but also when almost anything is constant. For example, the pressure-voltage ratio depends on constants of the basic circle diagram and the ratio $P'T/OT$. It is well known that the locus of a point the ratio of whose distances to two fixed points is constant is a circle.

The Damping of Large Amplitude Vibrations of a Fluid in a Pipe

R. C. BINDER
School of Mechanical Engineering, Purdue University, Lafayette, Indiana

(Received May 5, 1943)

Helmholtz and Kirchhoff developed a theory for the damping in space of the small amplitude vibrations of a fluid in a rigid cylindrical tube. Their work assumes laminar motion, and gives values which are very low for moderate and large pressure amplitudes. The present paper modifies the Helmholtz-Kirchhoff theory by the addition of an eddy viscosity term. This modified theory gives fair agreement with measured values of the damping of large pressure amplitudes for air and carbon dioxide.

THE damping of the vibrations of a fluid in a rigid cylindrical tube along its length may be appreciable and important for large pressure amplitudes. The damping may be negligible, on the other hand, for small pressure amplitudes. There is a fundamental question regarding the magnitude of damping factors over a wide range of conditions.

Helmholtz and Kirchhoff developed a theoretical analysis of the damping for laminar motion.[1] There is fair agreement between their theory and experimental results for very low pressure amplitudes. The limit of application of their theory has not been established. It is known, however, that the Helmholtz-Kirchhoff theory gives very low values of damping factors for large pressure amplitudes. No general method for predicting the damping factors for these latter cases is available. It would be helpful to have at least the order of magnitude of the factors.

The following treatment modifies the Helmholtz-Kirchhoff theory by taking into account inertia forces. The modified theory gives fair agreement with available experimental data.

THEORETICAL RELATIONS

The following notation is used:

a velocity of pressure propagation
c specific heat at constant pressure
d diameter of tube
k thermal conductivity
x distance along tube
z particle displacement
μ absolute or dynamic viscosity
ρ mean density of fluid
ω circular frequency

Consider any point x along a rigid cylindrical tube filled with an elastic fluid. For a wave traveling in the positive x direction, the particle velocity is

$$\frac{dz}{dt}=\dot{z}=A\exp[-\alpha x]\exp\left[i\omega\left(t-\frac{x}{a}\right)\right], \quad (1)$$

where A is a constant and α is a "damping" or "attenuation" factor. α has the dimensions of $(\text{length})^{-1}$.

Helmholtz derived the following relation for viscous action only:

$$\alpha=\frac{2}{da}\left[\frac{\omega}{2}\left(\frac{\mu}{\rho}\right)\right]^{\frac{1}{2}}. \quad (2)$$

Kirchhoff took into account the loss due to the heat conduction to the wall of the tube. His treatment showed that the thermal diffusivity $k/c\rho$ should be added to the kinematic viscosity, to give

$$\alpha=\frac{2}{da}\left[\frac{\omega}{2}\left(\frac{\mu}{\rho}+\frac{k}{c\rho}\right)\right]^{\frac{1}{2}}. \quad (3)$$

About the only available complete test results for large amplitude vibrations are those reported by Lehmann.[2] Other investigators have reported relative damping measurements, but they do not cover appreciable amplitudes, and they do not report the magnitude of the pressure amplitudes. Lehmann's experiments show that α is inversely proportional to $\sqrt{\rho}$. In this respect his results agree with the Helmholtz-Kirchhoff theory. On the other hand, the absolute values of Lehmann's results are considerably higher than values given by Eq. (3). There are indications that turbulence

[1] I. B. Crandall, *Theory of Vibrating Systems and Sound* (D. Van Nostrand, 1926), p. 229.

[2] K. O. Lehmann, Ann. d. Physik **21**, 533 (1934).

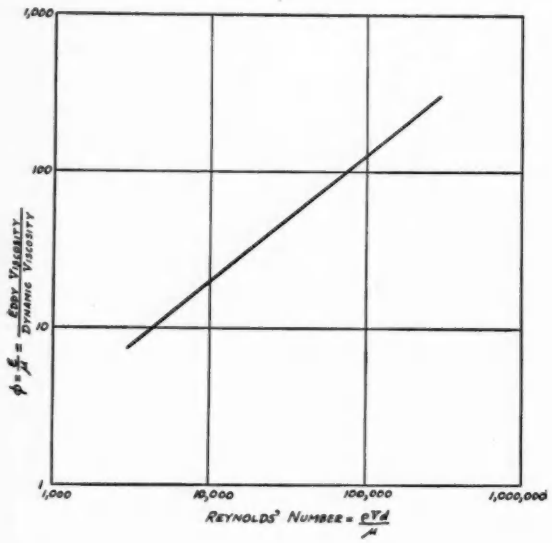


FIG. 1. Plot of Murphree's data for flow in smooth pipes. V = average velocity.

must be taken into account for the large pressure amplitudes.

TURBULENCE

Generally speaking, laminar flow is much more amenable to mathematical analysis than turbulent flow. The laminar, steady flow of a fluid in a circular pipe, and the laminar flow in a well-lubricated bearing are examples in which a rational analysis agrees closely with experimental results. The analysis of turbulent flow presents major difficulties. It is common practice to rely solely upon experimental results for investigating flow coefficients in the turbulent range. The problem, then, is to determine suitable parameters for correlating experimental results.

For laminar flow the shear stress τ is given by the expression

$$\tau = \mu \frac{du}{dy}, \tag{4}$$

where μ is the dynamic viscosity, and du is the infinitesimal velocity change in the infinitesimal distance dy. The ratio du/dy is the velocity gradient or rate of shearing strain. Equation (4) is commonly given in defining dynamic viscosity. For Newtonian fluids the dynamic viscosity is not a function of velocity gradient, but is a function of temperature and pressure. For turbulent flow the total shear stress can be written as

$$\tau = (\mu + \epsilon)\frac{du}{dy}, \tag{5}$$

where ϵ has the dimensions of dynamic viscosity. The factor ϵ has been called the "exchange coefficient," "mechanical viscosity," or "eddy viscosity." ϵ is not a physical characteristic constant of the fluid, like μ, but depends upon Reynolds number and other parameters.

Murphree[3] calculated values of the ratio between eddy viscosity in the main stream and dynamic viscosity for the steady flow through smooth circular pipes. This ratio is denoted by ϕ. His results, plotted in Fig. 1, show that the eddy viscosity increases with Reynolds number. The shear stress in turbulent flow may be considerably higher than that in laminar flow.

CORRELATION OF EXPERIMENTAL DATA

Eddy viscosity shows promise of being a useful parameter in determining values of α for large pressure amplitudes. Reynolds number for the damping in tubes can be written as $d\rho\dot{z}/\mu$. Taking $\dot{z} = p/\rho c$, where p is the pressure amplitude, this dimensionless Reynolds number becomes $dp/\mu c$. For a certain pressure amplitude,

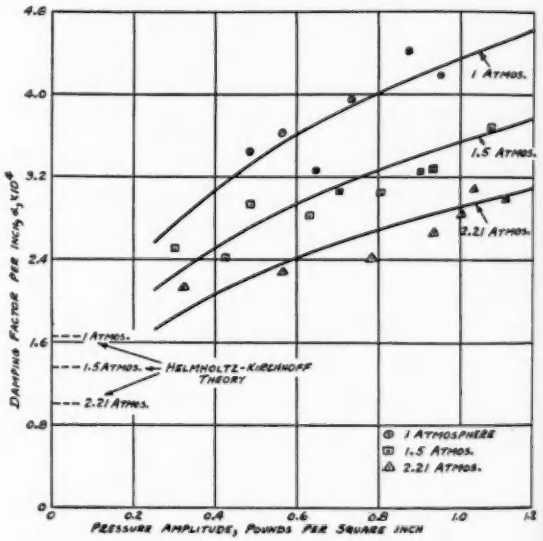


FIG. 2. Comparison between modified theory and experimental results for air. Points marked with circles, squares, and triangles are from Lehmann's experiments. Frequency is 50 cycles per second.

[3] E. V. Murphree, Ind. Eng. Chem. **24**, 726 (1932).

this Reynolds number gives a value of ϵ from Fig. 1. There is the question, then, of how the eddy viscosity should be introduced in the expression for α.

One possibility is to add the eddy viscosity to the dynamic viscosity in Eq. (3), to give

$$\alpha=\frac{2}{da}\left[\frac{\omega}{2}\left(\frac{\mu}{\rho}+\frac{\epsilon}{\rho}+\frac{k}{\rho c}\right)\right]^{\frac{1}{2}}. \tag{6}$$

Equation (6) was checked with Lehmann's experimental results. Equation (6) gave values of α which were higher than the experimental values.

Good agreement was found by modifying Eq. (6) with a factor 2π, to yield

$$\alpha=\frac{2}{da}\left[\frac{\omega}{2}\left(\frac{\mu}{\rho}+\frac{\epsilon}{\rho}+\frac{k}{\rho c}\right)\frac{1}{2\pi}\right]^{\frac{1}{2}}. \tag{7}$$

Equation (7) was employed to plot the solid curves in Figs. 2 and 3. Figure 2 shows a comparison of Eq. (7) with Lehmann's experimental results for air, and Fig. 3 shows a comparison for carbon dioxide. Lehmann gave α values ± 8 to 12 percent.

Figure 2 shows α *versus* pressure amplitude for mean pressures of 1, 1.5, and 2.21 atmospheres. The agreement between Eq. (7) and the experimental results is close. Figure 3 shows α *versus* pressure amplitude for mean pressures of 1, 1.61, and 2.17 atmospheres. With the exception of a few points at 1 atmosphere, the agreement between Eq. (7) and the experimental results is close. The case for 2.17 atmospheres gives particularly close agreement.

For air, with pressure amplitudes from 0.4 to 1.0 pounds per square inch, ϕ ranges from 48 to 98. For carbon dioxide, with pressure amplitudes from 0.4 to 1.0, ϕ ranges from 67 to 135. In these ranges viscous forces and heat conduction are relatively small factors.

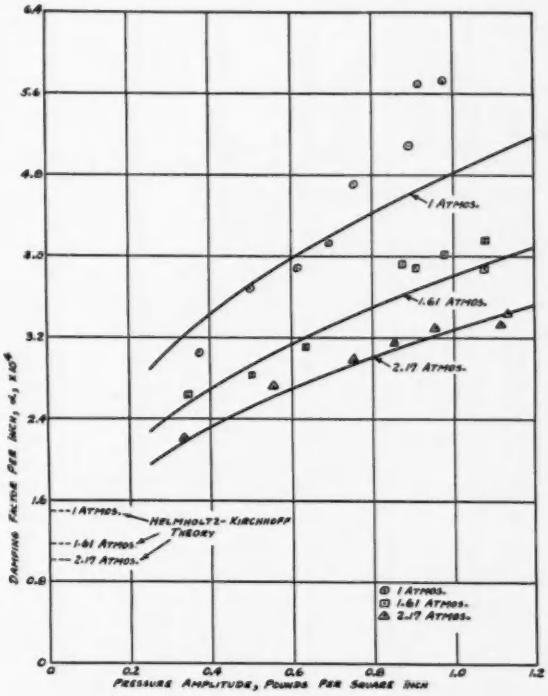


FIG. 3. Comparison between modified theory and experimental results for carbon dioxide. Points marked with circles, squares, and triangles are from Lehmann's experiments. Frequency is 50 cycles per second.

Equation (7) shows fair agreement with experimental data, for two gases at different mean pressures. Equation (7) provides a convenient method for predicting damping factors. More experimental results are needed. For one thing, there is the question of limits for laminar and turbulent motion. A complete, rational explanation of the mechanism of damping involves numerous difficulties. It seems as if the mechanism of turbulent motion must be established first, and then the additional complications due to the vibratory motion considered.

Conditions for Wide Angle Radiation from Conical Sound Radiators*

RICHARD W. CARLISLE
Sonotone Corporation, Elmsford, New York

(Received May 27, 1943)

The theoretical conditions by which substantially hemispherical radiation can be attained from the concave side of a loudspeaker cone are discussed and experimental data presented.

INTRODUCTION

THE general use of loudspeaker cones radiating from their concave side has developed from the broad experience in the loudspeaker industry, which showed that this type of sound radiator offered the most economical combination of power handling capacity, frequency range, and efficiency; but little experience has indicated that wide directional patterns can be secured at high frequencies.

It is the purpose of this paper to consider the theoretical possibilities of this matter and to show some data. It is hoped to demonstrate that the requirements for an ideal hemispherical radiator (to radiate over a wide angle in a home, for instance) can be satisfactorily met by one or two concave cones.

ANALYSIS OF CONE AS AN ARRAY OF PAIRS OF POINT SOURCES

It will be assumed that the vibrations of a cone are not all in phase, and that if the vibrational force is applied at the center, the vibration of bands or rings progressively spaced from the center will be progressively retarded in phase.

Let us consider a loudspeaker cone as shown in cross section in Fig. 1, and divide it into a series of bands or rings A, B, C, etc., spaced equally from the center. The bands are taken so narrow as to have several bands within one wave-length of vibration.

In the cross section of Fig. 1A, the rings A, B, C appear as pairs of small areas or points A, A', B, B', C, C', etc.

It may be seen that a plane radiation pattern can be calculated assuming that these pairs of points exist as point sources in the plane of the cross section of Fig. 1.

Since both the plane system of point sources and the three-dimensional array of rings are symmetrical about the central axis and have the same cross section, a solution of the plane array will show radiation patterns which will be characteristic of the three-dimensional array but altered somewhat in magnitude.

To illustrate this, directional characteristics have been plotted in Fig. 2:

(*a*) On the left, pistons having a ratio d/λ of $\frac{1}{2}$, 1, and 1.3,

$$R_\alpha' = \frac{2J_1[(\pi d/\lambda)\sin\alpha]}{(\pi d/\lambda)\sin\alpha}$$

as derived by Stenzel,[1,2] where d = diameter of piston and λ = wave-length of sound in air.

(*b*) On the right, pairs of points separated by a distance D such that $D/\lambda = \frac{1}{4}$ and $\frac{1}{2}$, for which $R_\alpha = \cos[(\pi D/\lambda)\sin\alpha]$.

This is derived later in this paper for the sake of completeness.[3]

By comparing the characteristics on the left side of Fig. 2 with those on the right, it may be seen that the directional curves for the disk for which $d/\lambda = 1$ to 1.3 closely resemble the curve for the pair of points for which $D/\lambda = \frac{1}{2}$, and similarly when $d/\lambda = \frac{1}{2}$ for a disk the curve resembles that for points for which $D/\lambda = \frac{1}{4}$.

This correspondence is considered sufficient justification for carrying out an analysis of a cone on the basis of pairs of points.

An empirical formula could be developed by using a factor of 2 to make the point formula numerically more expressive, but it was felt that the mathematical validity would not be enhanced by this change.

* Paper presented at the twenty-eighth meeting of the Acoustical Society of America, May 14–15, 1943, New York, New York.

[1] H. Stenzel, E. N. T. (June, 1927).
[2] H. Stenzel, E. N. T. (May 1929).
[3] For these formulae and references I am indebted to I. Wolff and L. Malter's classic paper, J. Acous. Soc. Am. 2, 201 (1930). The derivation to be given herein does not, however, follow theirs of Appendix A, Case (a).

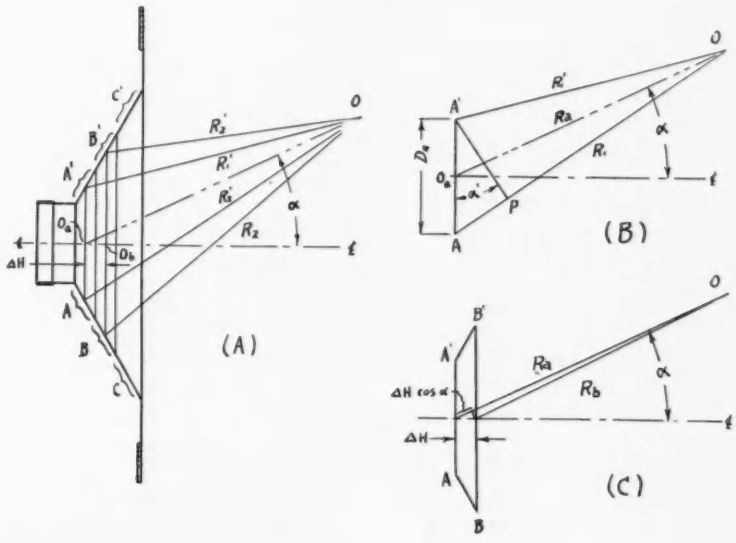


FIG. 1. Cross section of conical sound radiator.

The analysis of the array will be made by calculating the relative intensity of the radiation from points A and B in magnitude and phase at an arbitrary listener at a point O. The distance to this point is taken much farther from the cone than its own diameter and much greater than the wave-length of sound. The loudness at O will be equal to the vector sum of these intensities, and the variation of loudness as the dimensions describing the position of O are varied will describe the pattern of the radiation characteristic.

To make the analysis, we draw the rays AOA' and BOB' from the points A, A' and B, B' to the listener at O. The difference between the lengths of vectors AO and $A'O$ is evaluated by drawing the perpendicular $A'P$, as shown in Fig. 1B.

Let

D_a = distance $A-A'$,
D_b = distance $B-B'$,
α = angle between the central axis and the ray OO' from the middle of the cone to the observer, as in Fig. 2.

By similar triangles,

$$\alpha = \alpha'.$$

Referring to Fig. 1B,

$$AO - A'O = AP = D_a \sin \alpha.$$

Similarly,

$$BO - B'O = \quad D_b \sin \alpha.$$

The time phase angle ϕ_1 between vector AO and $A'O$ is the ratio of distance $D_a \sin \alpha$ (shown in Fig. 1B) to wave-length λ, which expressed

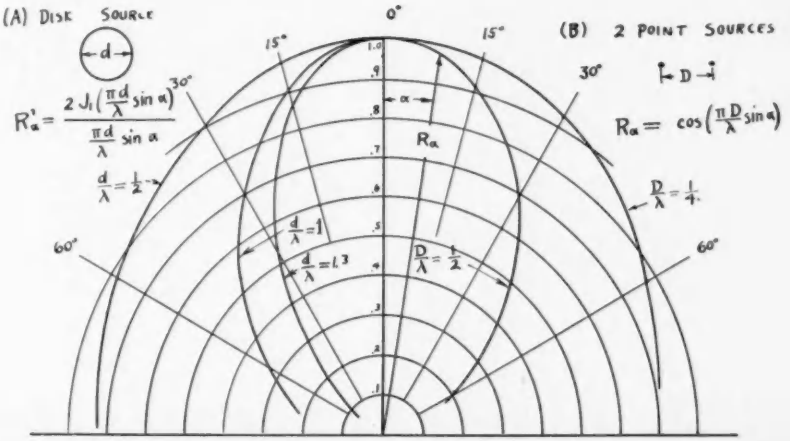


FIG. 2. Calculated radiation characteristics.

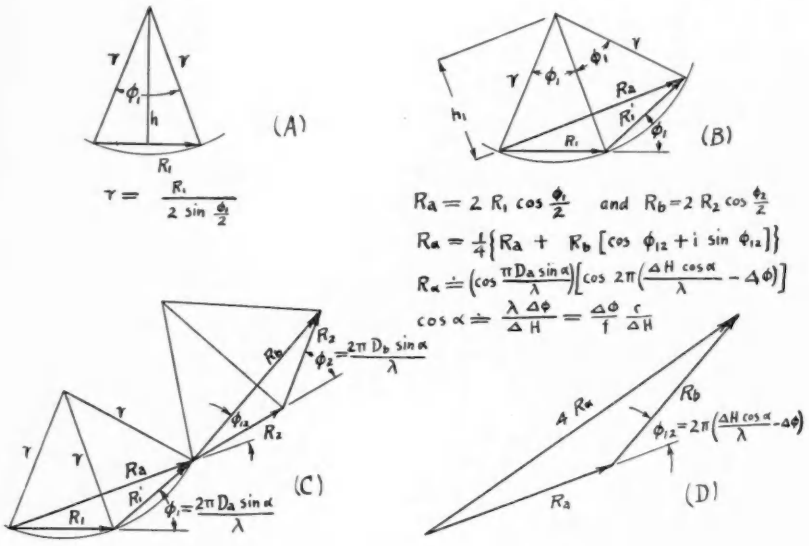


FIG. 3. Directional vector additions.

in degrees as indicated in Fig. 3B is

$$\phi_1 = 2\pi D_a \sin\alpha/\lambda.$$

Similarly

$$\phi_2 = \measuredangle BOB' = 2\pi D_b \sin\alpha/\lambda.$$

Referring to Fig. 1C, the two rings are separated by the axial distance ΔH. The component of this distance in the direction of O is $\Delta H \cos\alpha$. We assume $\Delta H \ll D_a$.

The time phase angle between rings expressed in degrees is the ratio of this distance to the wave-length, which expressed in degrees is

$$(2\pi\Delta H/\lambda)\cos\alpha.$$

The sound from B arrives at O before that from A according to the above relation, but is retarded by the amount of time retardation $\Delta\phi$. Hence the time phase angle for the vectors representing ring B relative to those for ring A is $\phi_{12} = 2\pi[(\Delta H\cos\alpha/\lambda) - \Delta\phi]$.

The vectors denoting the loudness and phase AO, $A'O$, BO, and $B'O$ will be termed R, R', R, and R, respectively. In the drawings, the relative length of these lines is not an indication of vector magnitudes.

The vector sum R_α as indicated graphically in Figs. 3B, 3C, and 3D may be expressed as follows, quantities being so taken that the maximum possible intensity of R_α will be unity:

$$R_\alpha = \tfrac{1}{4}\{R_1 + R_1' + R_2 + R_2'\}.$$

In these expressions the steady state time factor $(\cos 2\pi ft + i\sin 2\pi ft)$ has been omitted since it would appear only as a common factor in each vector and therefore not affect their relative phase and magnitude.

As shown in Fig. 3C, this may be evaluated as the sum of two pairs of vectors: R_1 and R_1' which are inclined to each other at an angle ϕ_1 and R_2 and R_2' inclined at an angle ϕ_2, the angle between pairs being ϕ_{12}.

As shown by trigonometry in Appendix A in connection with Figs. 3A and 3B

$$R_a = 2R_1\cos\frac{\phi_1}{2},$$

whence, substituting

$$\phi_1 = \frac{2\pi D_a}{\lambda}\sin\alpha,$$

$$R_a = 2R_1\cos 2\pi\frac{D_a\sin\alpha}{2\lambda}.$$

Similarly,

$$R_b = R_2 + R_2' = 2R_2\cos\frac{\phi_2}{2} = 2R_2\cos 2\pi\frac{D_b\sin\alpha}{2\lambda}.$$

Now

$$\underline{R_\alpha} = \tfrac{1}{4}\{R_a + R_b[\cos\phi_{12} + i\sin\phi_{12}]\}.$$

R_1 is a unit vector, and $|R_2|/|R_1| = I$, whence

as illustrated in Figs. 3C and 3D,

$$R_a=\tfrac{1}{2}\cos\frac{\pi D_a\sin\alpha}{\lambda}+\frac{I}{2}\left[\cos\frac{\pi D_b\sin\alpha}{\lambda}\right]$$
$$\times\left[\cos 2\pi\left(\frac{\Delta H\cos\alpha}{\lambda}-\Delta\phi\right)\right.$$
$$\left.+i\sin 2\pi\left(\frac{\Delta H\cos\alpha}{\lambda}-\Delta\phi\right)\right].$$

In order to demonstrate the relationship of the phase retardation of ring B to its position with respect to A, we will take rings so narrow that

$$D_b\doteq D_a \quad\text{and}\quad |R_2|/|R_1|\doteq 1 \quad\text{or}\quad I\doteq 1.$$

We will then have two equal vectors with a certain included angle as in Appendix A, whence

$$R_a=2R_a\cos\frac{\phi_{12}}{2}$$
$$=\left(\cos\frac{\pi D_a\sin\alpha}{\lambda}\right)\left[\cos 2\pi\left(\frac{\Delta H\cos\alpha}{\lambda}-\Delta\phi\right)\right].$$

The first term is the expression for the radiation pattern of a pair of point sources, separated by the distance D_a and radiating in phase. The pattern can never be broader than specified by this term, plotted in Fig. 2B. For pistons Fig. 2A is applicable.

In order to make this distribution vector R_a have as wide an angle as possible, we let

$$\cos 2\pi\left(\frac{\Delta H\cos\alpha}{\lambda}-\Delta\phi\right)\doteq 1,$$

whence

$$\cos\alpha\doteq\frac{\lambda\Delta\phi}{\Delta H}=\frac{\Delta\phi}{f}\frac{c}{\Delta H},$$

where c=velocity of propagation of sound vibrations in air.

This indicates that ΔH should be small and $\Delta\phi$ large between successive rings. This entails the use of a fairly flat cone, with mechanical properties of such a nature as to give a considerable retardation in phase.

This indicates also that the phase shift $\Delta\phi$ should be proportional to frequency if the radiation pattern is to be invariant with frequency.

This is precisely the type of phase shift which occurs in an iterative band pass filter.[4] A uniformly radiating structure may therefore be constructed of two groups of points (or alternatively, truncated conical surfaces) each having approximately the same mass, and resonating at some desired cut-off frequency with a compliant link between them, which may be a corrugation or a change in conical angle. A third section may be matched to the second in the same manner, and so on.

The nature of the mechanical construction required to give a large phase retardation per unit length of the cone will now be considered.

The phase retardation will be mathematically analogous to that in an electrical filter, so that the upper cut-off frequency is

$$f=1/\pi(MC)^{\frac{1}{2}}.$$

In the mechanical case

M=mass per section of mechanical filter,

C=compliance per section of mechanical filter.

The phase shift is substantially proportional to frequency and is 180° per section at the cut-off frequency.

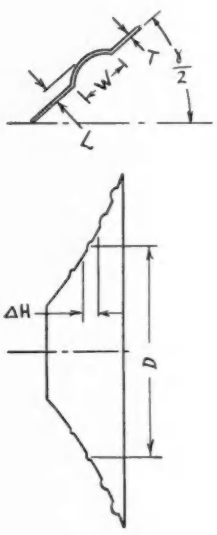
To secure an optimum phase shift, it is therefore essential to divide a given mechanical system into as many sections of mechanical filter as possible, and arrange the cut-off of each section to occur at the upper end of the frequency band to be utilized.

In interpreting this for the case of a cone, the effective mass of any portion of a cone can be readily measured or calculated, and the mass can be made greater or less by common construction methods. The compliance may also be analyzed and controlled.

Considering a cone having a point, the greatest compliance is undoubtedly near the point. The compliance is greater as the thickness is decreased. It is also greater for cones having larger solid angles and for cones constructed of soft, flexible material.

Much greater compliance can be secured by corrugating a cone. An empirical formula based on beam theory for the compliance of a semi-

[4] H. F. Olson and F. Massa, *Applied Acoustics* (Blakiston, New York), Chapter VII, shows a cone as an iterative structure. The derivation of the bend compliance for a cone follows that given therein for a corrugation in a cylinder.



$$\text{Compliance} \quad C = \frac{K W L^3}{D T^3 E \cos \frac{\gamma}{2}}$$

$$\text{Mass} \quad M = \frac{\pi D T \rho \Delta H}{\cos \frac{\gamma}{2}}$$

$$\text{Cutoff Frequency} \quad f_c = \frac{1}{\pi \sqrt{MC}}$$

$$f_c = \frac{K T \cos \frac{\gamma}{2}}{L^{1.5}} \sqrt{\frac{E}{W \rho \cdot \Delta H}}$$

$$\text{Iterative Impedance} \quad Z_0 = \sqrt{\frac{M}{C}}$$

$$Z_0 = \frac{K D T^2}{L^{1.5}} \sqrt{\frac{\rho E \cdot \Delta H}{W}}$$

FIG. 4. Propagation relations in portion of cone ΔH.

circular bead having rounded corners is:

$$C = \frac{KWL^3}{DT^3 E \cos(\gamma/2)},$$

where

W = width of bead,

L = bead height,

D = diameter of cone at bead,

T = thickness of material,

E = modulus of elasticity,

γ = angle included between walls of cone.

It is customary to make semicircular corrugations having sharp corners. These have no advantage over sine-wave shape corrugations except that the corrugating tools are easier to lay out. The compliance of these is apt to be a critical function of the sharpness of the edges of the bead, being less for sharply defined beads.

The mass per increment of cone height ΔH may be calculated assuming it to be a rigid frustum of a cone, thus

$$M = \frac{\pi DT\rho}{\cos(\gamma/2)} \Delta H, \quad \text{where} \quad \rho = \text{density}.$$

Let us consider the propagation in a portion of cone ΔH (Fig. 4). The cut-off frequency of mechanical propagation in the cone is

$$f_c = \frac{1}{\pi (MC)^{\frac{1}{2}}} = \frac{KT \cos(\gamma/2)}{L^{1.5}} \left(\frac{E}{W\rho \cdot \Delta H} \right)^{\frac{1}{2}}.$$

The iterative impedance is

$$Z_0 = \left(\frac{M}{C} \right)^{\frac{1}{2}} = \frac{KDT^2}{L^{1.5}} \left(\frac{\rho E \cdot \Delta H}{W} \right)^{\frac{1}{2}}.$$

It may be seen that the factors controlling the radiation angle in a cone are the same as those which experience indicates control the frequency range, i.e., higher frequency range is obtainable from a cone of narrow angle, considerable thickness, and small corrugations.

The factors which cause the pattern to be widened intrinsically limit the frequency range, and, therefore, a cone should be designed specifically for the range of frequency desired.

It can be shown graphically in the manner of Fig. 3 and it is well known that smaller cones have a wider radiation characteristic than larger ones. Experimental data on this taken by the writer show in Figs. 5A and 5B how much narrower a standard 8″ 105° corrugated cone characteristic is than a 3″ 130° corrugated cone. The improvement gained by corrugating the 3″ cone over using it without corrugations is shown in Figs. 5B and 5C. This cone was made of hard paper 0.0028″ thick, with a central angle of 130°,

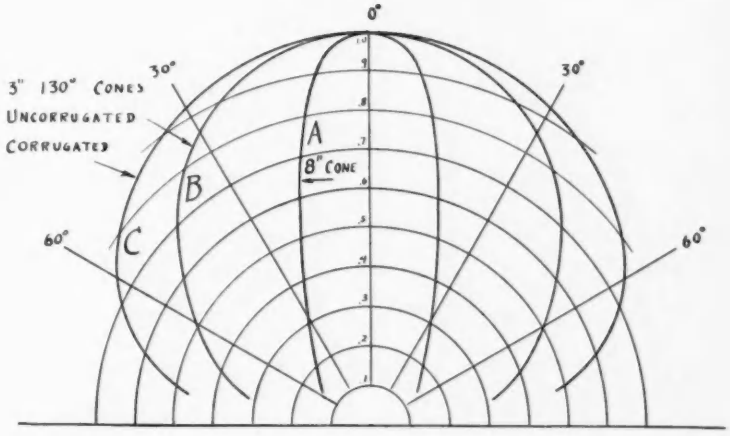


FIG. 5. Experimental radiation characteristics (3000 cycles).

a kid leather rim 3/16″ wide and 0.017″ thick, with 5 uniformly distributed corrugations, each approximately 0.015″ deep and 1/8″ wide, and semicircular in shape with well-rounded edges. The sound pressure characteristic of this cone was fairly flat to over 5000 cycles.

By comparing the curves for circular surfaces (Fig. 2A) with the experimental characteristics for the 3″ cones, it may be seen that the uncorrugated cone resembles a disk in which $d/\lambda=0.75$, approximately. At 3000 cycles, $\lambda=4''$, hence the effective diameter of piston is $d=0.75\times4=3''$.

For the corrugated cone, $d/\lambda=0.55$ approximately, hence $d=0.55\times4$ equals 2.2″.

The attention of experimenters is drawn to the possibilities of developing medium-size conoids combining a change in angle with increased depth of corrugations towards the outside. The change of angle should be small, since the middle portion should not be too steep or it will constitute too large a rigid piston, and consequently have a narrow directional characteristic; and the outer part should not be too shallow or it will rattle. From the above theory it would seem that by increasing the depth of corrugation L as the diameter D is increased, the impedance will be kept constant, thus making the phase shift as nearly proportional to frequency as possible, and high frequencies will be constrained to the middle of the cone (since the cut-off frequency will be lower for the outside portion) thus broadening the radiation pattern further.

CONCLUSIONS

The vector mathematics of radiation from an array of pairs of point sources has been approximately applied to a loudspeaker cone. The satisfaction of conditions of wide angle radiation has been shown to be possible by the control of mechanical propogation in the cone, this being accomplished by selection of the angle, the number and depth of corrugations, and the weight and stiffness of the cone material.

Curves of spatial distribution of experimental cones are presented.

APPENDIX A. DERIVATION OF EXPRESSION FOR THE SUM OF TWO VECTORS

Considering the equilateral triangle of Fig. 3A in which the base represents a vector such as R_1, let r be the radius of an arbitrary circle through the ends of the vector such that the angle included at the apex is ϕ_1. This radius r will first be evaluated in terms of ϕ_1.

If h is the altitude of the triangle,

$$R/2=(r^2-h^2)^{\frac{1}{2}} \text{ since } h\perp r,$$
$$h=r\cos(\phi_1/2),$$
$$\therefore\quad R_1=2[r^2-r^2\cos^2(\phi_1/2)]^{\frac{1}{2}}$$
$$=2r[1-\cos^2(\phi_1/2)]^{\frac{1}{2}}=2r\sin(\phi_1/2),$$
$$\therefore\quad r=R_1/[2\sin(\phi_1/2)].$$

Considering the diagram of Fig. 3B in which R_1 and R_1' are vectors disposed in the circumscribed circle of radius r each having the open angle ϕ_1, the vector sum is R_a.

Now

$$R_a/2=(r^2-h_1^2)^{\frac{1}{2}} \text{ since } h_1\perp\langle R_1+R_1'\rangle,$$
$$h_1=r\cos\phi_1,$$
$$\therefore\quad R_a=2(r^2-r^2\cos^2\phi_1)^{\frac{1}{2}}=2r(1-\cos^2\phi_1)^{\frac{1}{2}}=2r\sin\phi_1.$$

Substituting the value of r previously derived,

$$R_a=R_1[\sin\phi_1/\sin(\phi_1/2)]=2R_1\cos(\phi_1/2).$$

Mechanical Impedance Bridge*

A. M. WIGGINS
RCA Laboratories, Princeton, New Jersey
(Received May 27, 1943)

INTRODUCTION

BECAUSE of the complexity of the equivalent mechanical circuit of a phonograph pick-up and to the impossibility of determining the constants of the circuit with a very high degree of accuracy, it is sometimes desirable to determine the mechanical impedance of a phonograph pick-up at various frequencies by means of a measuring device. A mechanical impedance bridge for measuring the mechanical impedance of a phonograph pick-up for frequencies from 30 to 10,000 cycles is described below. The mechanical impedance bridge may also be used to measure the mechanical impedance of other vibrating systems as, for example, armatures, diaphragms, suspensions, etc.

DRIVING MECHANISM

If a reed, clamped at one end with the other end free, is driven at the clamped end by an alternating force, the displacement of the free end from the neutral position will be proportional to the applied force and the compliance of the reed. The force acting on the reed will be its effective mass times its acceleration. The effective mass of a reed clamped at one end is one-fourth its total mass. The mechanical circuit is a mass of one-fourth the total mass of the reed shunted by a compliance which is equal to $4L^3/Eba^3$, where L is the length, E the Young's modulus, b the width, and a the thickness of the reed. If two identical reeds are driven by the same force, the displacements of the free ends will be in phase and equal. Their relative displacement will, therefore, be zero. If one reed is then loaded with a mechanical impedance at its free end, the relative displacement will no longer be zero, but will be proportional to the driving force, the effective masses and compliances of the reeds, and the mechanical impedance of the load.

Schematic diagrams of the mechanical set-up and its mechanical circuit are shown in Fig. 1. The reeds are the ground plates of condensers. The high potential plates are fastened rigidly to the driving mechanism. A high potential is connected across the plates of the condensers through a high resistance and then to amplifiers using the conventional circuit of the condenser microphone. Since the compliances of the two reeds are the same, the ratio of the two forces is equal to the ratio of the outputs of the two amplifiers. The signals from the two amplifiers are mixed 180° out of phase; so when the reeds are driven with no load applied to either reed, the two

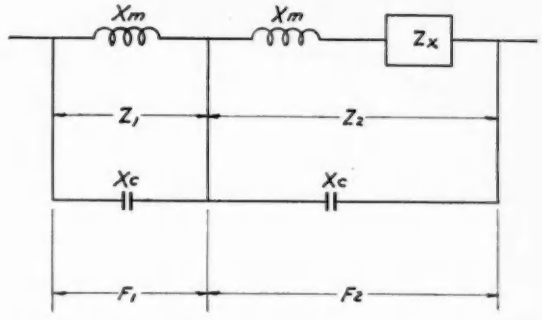


FIG. 2. Mechanical circuit showing impedances and forces.

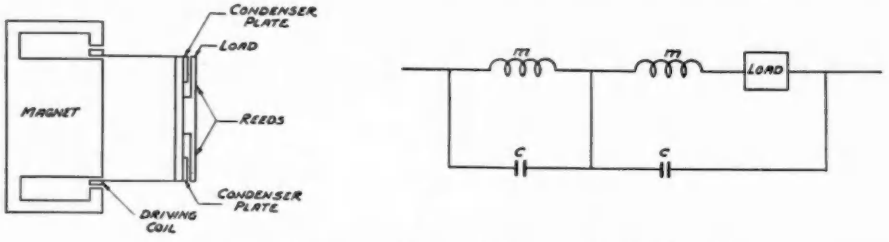


FIG. 1. Left, driving mechanism. Right, mechanical circuit.

* Paper presented at the twenty-eighth meeting of the Acoustical Society of America, May 14–15, 1943, New York, New York.

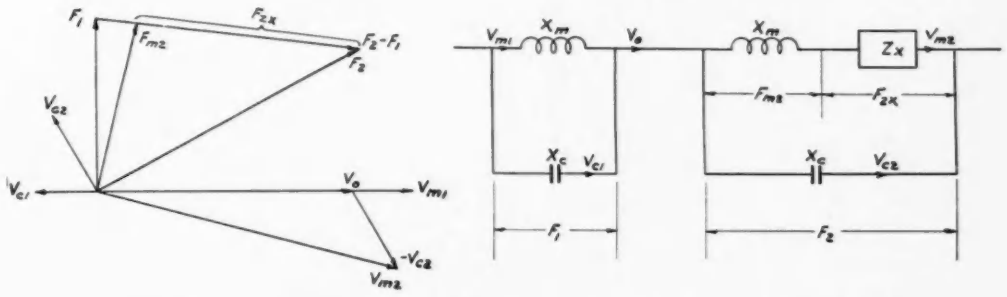


FIG. 3. Left, vector diagram. Right, mechanical circuit showing forces and velocities.

signals can be canceled. After the signals are canceled, and a load applied to the free end of one of the reeds, the mixed signal will be proportional to the vectorial difference between the force on the loaded reed and the force on the unloaded reed. The mechanical impedance of the load in mechanical ohms will be proportional to the ratio of the mixed signal with one reed loaded and the signal from the unloaded reed.

THE MECHANICAL CIRCUIT

From the mechanical circuit shown in Fig. 2, the unknown impedance of the load may be calculated using the ratio of the forces and the masses and compliances of the reeds. X_m is the reactance of the mass of either reed, X_c the reactance of the compliance, Z_x the unknown mechanical impedance of the load, Z_1 the equivalent impedance of the parallel mass and compliance, Z_2 the equivalent impedance of the mass of the reed in series with the unknown impedance shunted by the compliance of the reed, F_1 the force on the unloaded reed, and F_2 the force on the loaded reed.

$$Z_1=\frac{X_mX_c}{X_c+X_m},$$

$$Z_2=\frac{(X_m+Z_x)X_c}{X_c+X_m+Z_x},$$

$$Z_2-Z_1=\frac{(X_m+Z_x)X_c}{X_c+X_m+Z_x}-\frac{X_mX_c}{X_c+X_m}$$

$$=\frac{Z_xX_c^2}{X_c^2+2X_cX_m+X_m^2+Z_xX_c+Z_xX_m},$$

$$\frac{Z_2-Z_1}{Z_1}=\frac{Z_xX_c^2(X_c+X_m)}{(X_c^2+2X_cX_m+X_m^2+Z_xX_c+Z_xX_m)X_mX_c}$$

$$=\frac{X_cZ_x}{X_m^2+X_cX_m+Z_xX_m},$$

$$Z_x\left[1-\frac{(Z_2-Z_1)X_m}{Z_1X_c}\right]=\frac{(Z_2-Z_1)X_m}{Z_1}+\frac{(Z_2-Z_1)X_m^2}{Z_1X_c}.$$

If

$$\frac{(Z_2-Z_1)X_m}{Z_1X_c}\ll 1$$

which is true for frequencies well below the resonant frequency of the reed, the equation becomes:

$$Z_x=\frac{(Z_2-Z_1)}{Z_1}\left[X_m+\frac{X_m^2}{X_c}\right].$$

X_m is 180° out of phase with X_m^2/X_c; so eliminating the vector quantities and using only the numerical quantities, the equation becomes:

$$|Z_x|=\frac{Z_2-Z_1}{Z_1}\left[X_m-\frac{X_m^2}{X_c}\right].$$

Since $F_2/F_1=Z_2/Z_1$ the equation may be written:

$$|Z_x|=\frac{F_2-F_1}{F_1}\left[X_m-\frac{X_m^2}{X_c}\right].$$

If, however, $(Z_2-Z_1)X_m/Z_1X_c$ is not small in comparison to 1, the full equation,

$$Z_x\left[1-\frac{(F_2-F_1)X_m}{F_1X_c}\right]=\frac{(F_2-F_1)}{F_1}\left[X_m+\frac{X_m^2}{X_c}\right],$$

must be taken into consideration with the phase

FIG. 4. Mechanical impedance bridge.

relations. This equation will give the phase angle as well as the magnitude of the mechanical impedance. The calculation of the mechanical impedance for very many frequencies becomes an onerous task using this equation. The calculation may be done more easily by drawing a vector diagram of the mechanical circuit. The mechanical circuit and its vector diagram are shown in Fig. 3. V_{m1}, V_{m2}, V_{c1}, V_{c2}, and V_0 are the velocities of the various elements shown in Fig. 3 corresponding to the currents in the electrical analogy. In the vector diagram F_1, F_2, and $F_2 - F_1$ are drawn in their proper phase relation from the values of their magnitudes. V_{m1} is then drawn at right angles to F_1, lagging by 90°, and is proportional in magnitude to $1/X_m$. V_{c1} leads F_1 by 90° and is proportional to $1/X_c$. The vector sum of these two velocities is V_0. V_{c2} is drawn leading F_2 by 90° and is proportional to F_2/F_1X_c. By subtracting V_{c2} from V_0, V_{m2} is obtained which is proportional to the velocity of the unknown impedance. F_{m2} can now be drawn at right angles to V_{m2} and leading by 90°. The point at which it intersects $F_2 - F_1$ will determine its magnitude. $Fz_x = F_2 - F_{m2}$ which is the force on the unknown impedance. The unknown mechanical impedance, Z_x, is proportional to Fz_x/V_{m2} taken from the vector diagram. Since X_m is proportional to F_{m2}/V_{m2}, then $Z_x/X_m = Fz_x/F_{m2}$. The phase angle of the mechanical impedance is determined by the phase angle between Fz_x and V_{m2}.

CONSTRUCTION

The driving mechanism should not generate too high a percentage of harmonics and should be free of rattles. If the driving mechanism generates a small component of the natural frequency of the reed, the reed will vibrate at its natural frequency. The driving mechanism should also be as free from rocking as possible. Any rocking movement will cause the reeds to be out of phase by a small amount resulting in the inability to cancel the no load signals. Since at some frequencies there will be some rocking in the driving mechanism, provision was made for shifting the phases of the two signals in the amplifiers. These phase shifting circuits are low pass filters; so they will attenuate frequencies above the fundamental more than the fundamental, thereby attenuating the effect of any rattles or harmonics.

For frequencies above about 500 cycles per second, the reeds should be made of aluminum; while for frequencies below this value they may be made of brass. Care should be taken to clamp the reeds rigidly. In order to do this, the two reeds were made as one piece as shown in Fig. 1.

The mechanical impedance bridge is shown in Fig. 4. The two meters read the values of the displacements of the reeds. A switch is provided so that one meter reads either the mixed signal of the two reeds or the signal from the top reed alone. The other meter reads the signal from the bottom reed alone. A powerful driving system capable of handling 25 watts at the high frequencies with the driving coil mounted on a

FIG. 5. Driving mechanism.

rubber support was used. Considerable more power is needed at the high frequencies because of the low compliance of the reeds used at these frequencies. A close-up of the driving mechanism with the top reed loaded is shown in Fig. 5. The support for the pick-up can be adjusted for any length tone arm.

OPERATION

A reed whose natural frequency is somewhere above 1.5 times the frequency at which the measurement is to be made is generally acceptable. The proximity to the natural frequency at which a measurement can accurately be made, depends on the value of the mechanical impedance of the load; the smaller the value of mechanical impedance the closer to resonance the reed may be operated. After the desired reed is selected the amplifiers are turned on, and a signal from an oscillator and power amplifier is impressed across the driving coil. The reading on the meter for the mixed signal is brought to zero, and the load applied. The meter then reads the value F_2-F_1, while the other meter reads F_1. The mechanical impedance may now be calculated from the equation:

$$Z_x=\frac{F_2-F_1}{F_2}\left[X_m-\frac{X_m^2}{X_c}\right].$$

In order to facilitate the calculation of the mechanical impedance by this equation, curves are plotted of $X_m-(X_m^2/X_c)$ *versus* frequency for every reed; so the ratio $(F_2-F_1)/F_1$ may be multiplied by this quantity as taken from the curve. If a vector diagram is desired, F_2 may be obtained by turning a switch, so the meter reads the signal from the loaded reed alone. From the values of these three meter readings, the three forces may be plotted in their proper phase relations, and a vector diagram drawn from which the mechanical impedance may be calculated. For most measurements, the quick and easy method of calculating the impedance by the formula and the ratio of the two forces will give sufficient information.

THE JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA VOLUME 15, NUMBER 1 JULY, 1943

Direct Observations of the Acoustic Oscillations of the Human Ear

H. G. KOBRAK
Department of Otolaryngology, University of Chicago, Chicago, Illinois
(Received May 20, 1943)

DURING the last eighty years, all work on the function of the ear is based on, or at least is influenced by, the fundamental work of Helmholtz. Notwithstanding many contradictions and in spite of numerous unexplainable findings, the Helmholtz theory of hearing is still the leading theory on the function of the ear. But as the term "theory" is used, it is made clear that our teaching of hearing mechanisms is not based on direct observations, but on interpretations of anatomical studies and animal observations. It would be an important step forward to make parts of the living human ear available to direct observation during the process of hearing. A direct recording of the facts would end the hearing "theory" and replace it by an accurate description of a physiological "Geschehen."

All accepted hearing theories speak of forced vibrations of certain parts of the ear. While nobody has actually seen these vibrations, the anatomy of the ear makes these vibrations very plausible. The magnitude of these acoustic vibrations has been considered infinitesimally small.

In this experimental work the attempt was made to develop a method of satisfactory sensitivity to visualize the acoustic movements of the ear. The method was developed in four principal steps: (1) proper exposure of the anatomical structures under study; (2) proper illumination; (3) proper magnification; and (4) proper retardation (stroboscopic illumination).

The acoustic stimulus is produced in an oscillator and conducted through a closed tube system to the ear. A Siegle's speculum was used in the auricle to lead the sound into the outer acoustic canal. The presence of resonance phenomena in such a system can be expected and has been actually observed, but does not interfere with qualitative demonstration of the acoustic movements in the ear. Illumination was provided by reflected light (concave mirrors). The problem of magnification found an astonishingly easy solution. It was anticipated that only a high powered magnification would visualize the tympanic oscillations. However, it was found in pre-studies on both human cadaver specimens and on living animals that the amplitudes of the eardrum and the ossicles for loud tones are large enough to be seen with simple magnifying lenses. A lens of about 12 diopter meets the optional requirements sufficiently. Most Siegle's specula are equipped with such a lens. This instrument was therefore useful not only for the introduction of the sound into the outer ear canal but also provided the necessary magnification. It is essential to throw the light into the outer ear canal in such a way that it runs parallel to the walls (Fig. 1) and is reflected on the eardrum and returns to the camera again without being absorbed or deflected by the walls. The presence of the head of the observer or of the camera makes it impossible under ordinary circumstances to have the light shine into the canal directly. The difficulty is overcome by using a mirror with a hole in the middle. The camera "shoots" through the hole, while the light goes parallel to the axis of the camera. A concave mirror of proper dimensions and dioptric power is attached to the camera but is movable in all directions apart from the camera (Fig. 2). The Siegle's speculum consists of a funnel (*A*) which is inserted into the outer ear. The sound enters through the opening (*B*) while a lens (*L*) provides magnification (Fig. 3). The usual strength of the lenses employed is +11 to +13 diopters. The stroboscope used in our experiments consisted of a motor driven disk into which a certain number of holes were driven.

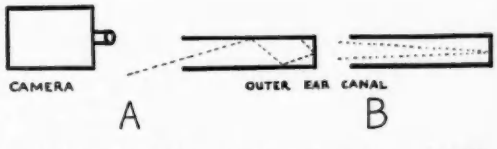


FIG. 1. Principle of illumination of eardrum. (A) Wrong. Light thrown in from beside the camera is reflected and absorbed by the walls of the outer ear canal. (B) Right. The light waves are reflected by the eardrum and reach the camera without striking the walls of the outer ear canal.

The speed of the motor and the number of holes can be changed so that several frequencies can be observed. If the number of interruptions equals the frequency of the tone, the ear appears to stand still. If the two are nearly equal, slow movements are seen.

The complete arrangement of the method is given in Fig. 4. This method was used on fresh human cadaver specimens and on ear normal persons as well as on patients suffering from deafness.

For qualitative observation the direct observation of the acoustic vibrations of the tympanum or their recording by a camera is satisfactory. For quantitative work optical recordings were used. A small mirror was attached to the ear drum or the malleus and the deflection of the light beam due to the acoustic vibration measured. Mirrors were placed on the neck of the hammer and on the body of the incus in cadaver specimens. In the living human, a mirror can be placed on the eardrum without much difficulty and without any damage to the ear (Koehler).

DISCUSSION OF RESULTS

It was demonstrated experimentally in this work that loud tones produce enforced vibrations of the tympanic membrane and ossicles which

FIG. 2. Diagram of light source, perforated mirror, and camera.

are (in stroboscopic light) visible under low magnification. These vibrations were observed on ear normal persons and on patients suffering from various degrees of deafness. In cadaver ears it is possible to show the acoustic movements of the stapes and even of the basilar membrane of the cochlea. Similar results are obtained in animals. The acoustic stimuli used in these experiments were for demonstration purposes rather loud, but not excessive and definitely below the threshold of feeling. Once the phenomena is known and the experimental method developed it is possible to visualize movements at much lower intensities than those used in the preparation of the moving picture film. Direct observation makes it unnecessary to speculate on the mode of vibration of eardrum or ossicles as has been done in the literature previously. It is also hoped that the problem of sound conduction through the air of the middle ear cavity

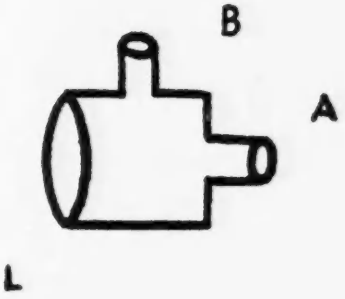


FIG. 3. Siegle's speculum, which was used to conduct the sound into the outer ear under simultaneous observation of the eardrum. (A) Funnel which is inserted into the outer ear canal; (B) Connection through which the sound enters the chamber of Siegle's speculum; (L) Lens for magnification of eardrum.

and its relative importance can be solved experimentally.

Optical recording with mirrors attached to the ossicles (cadaver specimens) permits a quantitative study of the amplitude of vibrations due to various acoustic stimuuli. The rotation of the malleus as the function of tone intensity can be shown on curves. It can be demonstrated that Hooke's law is first obeyed until a certain critical intensity is reached, after which a non-linear function begins.

The findings should be interesting to the *physiologist* because they show the amplitude of the over-threshold tones, an amplitude which apparently was misjudged by most physiologists. Our thinking had been concentrated too long on the threshold of hearing.

The *otologist* should be interested because a method is offered to compare the vibrations of a normal ear with that of a diseased ear.

Finally the manufacturer of hearing aids

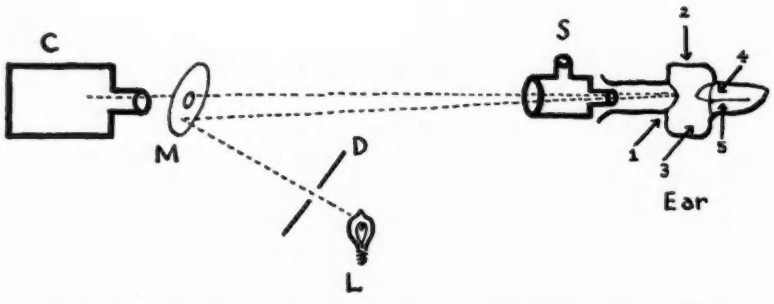


FIG. 4. Schematic diagram of the method. (*L*) Light source; (*D*) Motor driven disk with holes (stroboscope); (*M*) Mirror; (*S*) Siegle's speculum; (*C*) Camera. The light produced at *L* passes through the stroboscopic disk (*D*), is reflected on the mirror (*M*), and passes through the Siegle's speculum (*S*). The sound is introduced through the upper opening. The light, after passing through the chamber of the Siegle's speculum, is reflected by the eardrum. The reflected light passes through the hole of the perforated mirror and enters the camera. In the living human being observation is confined to the eardrum. In cadaver specimens additional observations are possible (indicated by arrows). Arrow 1 indicates observation of eardrum through a hole in the outer ear canal. Arrow 2 indicates exposure through a hole made in the tegmen tympani (roof of middle ear cavity). Arrow 3 indicates observation of round window membrane through opening in floor of middle ear. Arrow 4 indicates observation of stapes footplate. Arrow 5 indicates observation of basilar membrane.

should be interested because they show how great the amplitude has to be in order to be heard with a certain loudness and how great the amplitude can be without being unpleasant or painful.

THE JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA VOLUME 15, NUMBER 1 JULY, 1943

Is the Threshold Audiogram Sufficient for Determining Hearing Capacity?

EDMUND PRINCE FOWLER
New York, New York

(Received May 15, 1943)

FROM time immemorial hearing acuity has been thought of, and in fact measured, in terms of the distance at which a sound could be heard. This ancient practice would be accurate if it were not for the great distances often involved and the difficulty in controlling environmental factors which interfere with its accuracy.

Some twenty-two years ago the first practical audiometer was made available for otological and research purposes.[1] Its calibration, frequency, and intensity scales and its recommended method of use have been changed but little, if any, in the interim. Otologists still use the audiometer almost exclusively for determining threshold values, the minimum detectable intensities at any and all frequencies. In other words, the audiometer is used as another way and a more accurate and easy way of determining hearing distance. The question is, are threshold values dependable as an over-all measure of hearing capacity.

Not only for hearing but also for all the senses (touch, smell, pain, temperature, taste, position, sight, and hearing), quantitative measurements of sensitivity have been predicated on the threshold response to the stimulae applied as compared to the average normal threshold of sensitivity. It will be shown that threshold determinations alone are not sufficient for measuring *what* an animal, or a person, senses, or how much he is capable of sensing. It will be demonstrated that the threshold audiogram, although determining definitely what a person cannot hear, is not sufficient for determining how much he can hear.

The otologist is under a great debt to the physicists and acoustical engineers for their contributions of accurate measuring machines for testing hearing and for studying the physiology of the ear, but the hearing mechanism is not just an electrical hookup, a transmitting and transforming system for changing electrical potentials. It is more complicated than this: It functions not only to enable the animal, and particularly the human animal, to be conscious of the sound sensation of the moment, but coincidentally to store up what we call "memories" for future reference and comparison, and for further use in connection with reactions coincidental to the environments which produce and reproduce them, and for anticipatory protective or preventive action.

Without memory there is no melodic vocalization or articulate speech, or any understanding of melody or speech. Without memory the only sensation that can be communicated is the feeling or tone sensation of the moment. These feelings are phylogenetically so deeply rooted and instinctive that no conditioning is necessary in their expression. They are possessed by even the new born babe. Memories of the exact grade and differences in pitch, loudness, timbre, and timing gradually fade. Sometimes all that seems necessary is to remember that there are differences and the original symbolic concepts with which they were related. The brain seems able to recognize speech even though only a portion of the normal pattern is received. In some such way very far distant speech is heard; in this way the hard of hearing person hears and remembers speech.

I believe it will be well for me to confine my discussion largely to the clinical, rather than to the mechanical aspects of the question. In man even the slightest and simplest frequency sensation (the pure tone) is inexorably linked with psychic factors. Complicated sensations like music and speech, are highly linked with psychic factors. It is impossible to disassociate the hearing from psychological factors. To make matters still more complicated, no one knows what someone else is really hearing or even how his own speech or singing voice sounds to others; this latter, incidentally, may account for some of the terrible singing inflicted upon us from time to time. Listen to your own voice reproduced from

[1] E. P. Fowler and R. L. Wegel, Trans. Am. Otol. Soc. 16, 105 (1922).

a recording. Your friends recognize it readily, but do you if you do not recognize the words you have spoken, or if you are not expecting to hear your own voice?

Even normal hearing individuals choose different volumes, timbres, inflections, and cadences as being most agreeable or convenient to themselves and to others, or as most efficacious. In other words, no two people speak exactly alike or hear exactly alike, or can be made to speak or hear exactly alike. Moreover, people frequently do not listen. It is often true that "Grandma can hear if she wants to hear." Have you not ignored the family radio roaring forth some blatant advertising twaddle or undesired program, while you are reading or writing with concentration? Your brain has shut out the undesired or unwanted sounds by refusing to pay attention to them. If you were successful in testing the hearing of some one who is doing this, his threshold would be found very high indeed. And yet such a "mental deafness" may occur in a person with perfect hearing. In fact, it is a sign that the higher or psychic neural mechanism of hearing is in good working order, no matter how much basic deafness exists.

The threshold audiogram is a graph of minimum audible intensity at the specified frequencies. It is drawn 1 db above maximum subaudible intensity. It, therefore, definitely shows in full the intensities that are not audible (all that have gone out), and all the intensities that can be heard (all that are still coming in), but not how well they can be heard in different combinations or at different levels above threshold. It shows more the debit than the credit side of the ledger of the hearing function. Lack of sensation is a very definite thing. It is a blank. But degree and quality of sensation vary with many factors and do not necessarily correspond to the intensity of the stimulus.

We do not know exactly what an animal hears (or what he sees, or smells, or tastes, or feels) when he responds to sound stimuli. Often we do not know whether he hears anything, or whether he is reacting to some tactile sensation other than sound, to some coincidental disturbance, and not to sound at all.

It is pretty certain that no animal experiences the same sensations as a human being, and that he does not even experience the exact sensation of another of his own species. No two animals hear, see, smell, taste, or touch alike. If they did there would be little or no choice between them.

We do know that threshold sensations are generally ignored. In order to be heard at all they require much greater concentration, or conditioning, than sensations well above threshold.

The brain seems especially conditioned to use moderate intensities although these also may be unnoticed or psychically wholly ignored. Practice may improve the level of response, to as much as 10 or 15 db and in some instances even more.

There is almost always some environmental noise and this causes an elevation of the threshold for sounds near or above the masking frequencies, because all sounds contribute their share mechanically and psychologically to masking out other sounds, whether the latter are desired or not.

The acuity of perception, as well as of production of speech, varies greatly with emotion, age, sex, race, etc., but no one intentionally speaks very faintly if he wishes to be understood. The tendency usually to ignore faint sounds conserves well being. It avoids making useless readjustments to trivial changes in the internal or external noise environment.

It is not the exact frequency of speech which is of the most importance for understanding it, because "speech frequency bands" may shift up and down over two or more octaves and still be perfectly understood by a normal hearing person. It is more the associated loudness, frequency, accented and cadence patterns of the speech, that are fundamental for understanding speech. Even if all the speech frequencies are heard at threshold few if any words can be understood, because speech consists of sounds of greatly varying intensity.

It is physically impossible to maintain one's soft or loud voice at a given level of intensity and timbre in testing the hearing for speech, because the voice automatically changes in loudness and in timbre with psychosomatic states, extraneous noise, and with distance from the patient,[2] and with his difficulty in hearing it. Everyone

[2] E. P. Fowler, Jr., Acta Otolaryngol. **28**, 283–304 (1940).

automatically speaks louder in a noisy place and the farther he is away from the one to whom he is speaking. If he does not do this he knows he is apt not to be heard. Fatigue and the degree of the patient's cooperation often cause variations in the examiner's voice. These are some of the reasons why the natural human voice is not well adapted to accurate testing.

Sound reaches the inner ear, in which is situated the neural end organ of hearing, by two methods of transmission through the head. First, by what is called air conduction and, second, by what is called tissue or bone conduction. Both are really inseparable because each sets up the other no matter how the sound is brought to the ear or head. However, they normally differ relatively in amount and vary greatly with the position, extent, and pattern of the lesions causing deafness.

Impedance lesions confined to the conducting apparatus usually cause no loss of bone conduction, because they do not basically affect the neural mechanism of hearing. Nerve lesions confined to the neural apparatus of hearing—although they cause a loss by both air and bone conduction, have no damaging effect upon the conducting mechanism of hearing. In one instance the hearing is impaired only for sounds heard through the air. In the other the hearing is impaired for sounds heard through the air or through the bones of the skull. In neither is the hearing impaired to the same extent or in the same way, *even though the threshold losses may be similar*. In both, the threshold surely shows only what cannot be heard.

In pure obstructive lesions all frequencies may be clearly heard if sufficiently amplified, but whenever the voice is greatly amplified its timbre seems changed even to a normal ear. With what is known as selective amplification it is possible partially to smooth out the greater threshold irregularities in the speech frequencies for the deafened person, but for a normal hearing person, the more you alter the natural frequency intensity pattern of origin, the more distorted will be the reception. However, some selective adjustments are possible although in no instance can they be compared to the accurate correcting of refraction disorders of the eye by properly fitted lenses. Neither with the eye or the ear is it possible to bring back perfect sensation in the nerve loss areas by selective corrections or otherwise.

One difficulty in obtaining a percentage of hearing loss for the spoken word comparable with a percentage seeing loss for the written word is that the ear contains no mechanism similar to the focusing apparatus of the eye. Hearing for near and far sound is not primarily dependent upon a change in focal distance. The normal ear has a universal range limited only by the intensity of the sounds reaching it from all directions.

The immobilized eye cannot see anything behind it. However, in both the eye and the ear there is what may be called a peripheral sensation, a seeing or hearing for background or environment. One can in some manner ignore these peripheral or background effects if he is concentrating upon central vision, or on what is sometimes called central hearing (the sound which one is particularly desirous of understanding). One cannot, however, ignore the masking effects of environmental noise as easily as the masking effects of environmental images, because central vision is usually more intense and clear and more easily concentrated upon than "central hearing." It is more acute than peripheral vision for equal intensities, whereas the so-called "central" and "peripheral hearing" are equally acute for equal intensities.

Articulation percentage tests done as they have been under artificial conditions with apparatus, while valuable, are if done under static environment and distances, not of universal application because no one usually hears conversation under static conditions or at set distances. Hearing distance and environment are constantly changing. A person may hear nearly everything one is saying at a distance of 4 feet[3] (or less), and the next moment be unable to hear anything intelligibly because you are 5 feet from him or because some other sound enters the sound field. There may be practically no loss at 4 feet and nearly 100 percent loss at 5 feet or in the presence of the masking sound.

[3] This is like measuring eyesight by reading the newspaper at 16 inches. We normally do read at 16 inches almost 100 percent of the time. But we do not listen to near speech at 4 feet or 5 or 6 feet or any other distance 100 percent of the time.

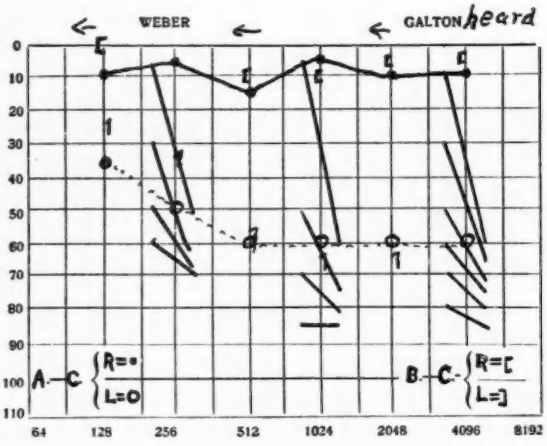


FIG. 1. Graph showing near normal hearing in the right ear and losses in the speech frequencies in the left ear of from 50 to 60 db. When the right ear was masked there was no hearing for speech in the left ear. Both the bone conduction loss in the left ear and the presence of the "recruitment" phenomenon clearly indicate a nerve deafness. The oblique lines drawn across the ordinates at 256, 1024, and 4096 illustrate the binaural loudness balance at these frequencies. The ends of each line drawn across the ordinates plot the equal loudness levels in decibels. The "recruitment" phenomenon was also present at all of the other frequencies, but for clarity was omitted from the graph. The patient can hear all the frequencies, and he can hear the speech sounds in the left ear, but the loudness and articulation patterns are so distorted that no words can be understood when the opposite (good ear) is masked. He is suffering from a monaural total deafness for speech with only a moderately severe deafness as shown by the threshold response. He is also suffering from a neural deafness which gives rise to the "recruitment" phenomenon. It is evident in this instance that the air conduction audiogram was not reliable as a measure of the capacity of the patient to hear any sounds above threshold (any of the frequencies, or speech).

How then can we estimate an over-all loss for speech? Only by setting up arbitrary standards based on average experience. There are several ways to do this. I did it as follows: I obtained the opinions of some 500 normal and hard of hearing people as to their estimates of the relative importance of near speech, telephone speech, medium speech, and distant speech.[4] It was interesting to note that the estimates of the normal and hard of hearing were similar. I also determined the length of time each day that people listened to near, telephone, medium, and far speech. Hundreds of people were tested by the voice and compared to the Steinberg and Gardner percentage of articulation tables. Air conduction and bone conduction and the "Recruitment Phenomenon" were all carefully studied and all the data were incorporated into "A Method for Measuring the Percentage of Hearing Capacity for Speech." In practice the method has given a closer approximation of the clinical picture than any other I have seen. To be of service any standard must closely approximate the clinical picture. This method was presented before your Society and published in *The Journal of the Acoustical Society of America*.[5]

In addition to the phenomena heretofore discussed there are three which the threshold audiogram does not reveal. I refer to the recruitment and blurring phenomenon encountered in neural acoustic lesions, and to binaural and monaural deafness for words ("word deafness" and "monaural speech deafness"), but not for other sounds.

The effect of the recruitment and blurring phenomena on the hearing for speech was discussed at length last year. These phenomena are real hazards to be overcome in any method for measuring the hearing. They are usually neglected not only by most acoustic engineers but by otologists as well. Almost every one accepts the air-conduction threshold audiogram as sufficient for determining hearing capacity, whereas, as I have demonstrated, it certainly is not.

Binaural "word deafness" may be congenital or acquired, the hearing at all frequencies may be normal and yet there is no hearing for speech. "Monaural speech deafness" is a phenomenon I have recently reported. It is a condition in which there may be a total deafness for speech in one ear but not sufficient loss of hearing at the speech frequencies to account for it.[6] The opposite ear may possess perfect hearing for speech. It is evident that in neither of these conditions does the threshold audiogram give even an inkling of what the ear is capable of hearing. Figure 1 illustrates several of the phenomena under discussion. Admittedly there are others which are not revealed by the threshold audiogram alone and not as yet well understood by the physician and the physicist or the otologist.

[4] Suggested by Mr. J. E. Steinberg and reported before this Society and the A.M.A. last year.

[5] J. Acous. Soc. Am. **13**, 373 (1942).

[6] To be published.

Scientific Research and Political Regulation

MEMBERS of the Acoustical Society will do well to give considerable thought to Senate bill S.702 which is published in the May 7, 1943, issue of *Science*, and, we understand, will be published in *The Review of Scientific Instruments* for July. This is described as a bill, "To mobilize the scientific and technical resources of the Nation, to establish an Office of Scientific and Technical Mobilization, and for other purposes."

The bill, if passed, would affect very materially the future careers of all scientific men and development engineers. It supplies machinery for the control and coordination of research, including inventions, and would also have a considerable bearing on education in the sciences and technologies.

While it may be supposed that this bill presents an unduly pessimistic view of the adequacy of present mobilization of science for the purposes of war and peace and is unlikely to meet the approval of Congress, its emergence should be regarded as a symptom of an underlying trend towards the socialization of research and education. The questions involved are very profound and very important. Scientists and engineers, whether or not they are concerned about the bill S.702, should take steps to inform themselves concerning the future relationships of their professions with the federal government and the factors which are likely to determine what these relationships will be. Having obtained information on the basis of which to form conclusions, scientists and engineers should not hesitate to make their voices heard whenever questions of national policy or of proposed legislation in these respects arise.

In regard to certain limited aspects of the bill, the War Policy Committee of the American Institute of Physics recently passed a resolution which is as follows:

WHEREAS, the American Institute of Physics, representing the physicists engaged in all branches of activity in their profession, has made studies and surveys to determine the extent to which physicists are engaged in and contributing to the war effort; and

WHEREAS, the facts thus found show that practically all physicists are now applying themselves to the advancement of war research, war industry, and training personnel for the war effort; therefore

BE IT RESOLVED that the War Policy Committee of the American Institute of Physics, while conceding that there is room for improvement, nevertheless maintains that physics is well mobilized and is effectively working on the problems arising out of the war through such agencies as the Office of Scientific Research and Development; the laboratories of industry and of the various branches of the armed services and other government agencies; and in the laboratories and classrooms of our educational institutions where large numbers of personnel are being trained for war service; and

BE IT FURTHER RESOLVED that the War Policy Committee of the American Institute of Physics regards the proposals now before Congress in the forms of Senate bill No. S.702 and House bill No. H.R. 2100 as not well conceived to increase the productivity of physics in the war, but rather tending to disorganize and retard the effective work now being done.

H. A. B.

Acoustical Society News

Meetings

The twenty-eighth meeting of the Acoustical Society was held in New York on May 14 and 15, with a registered attendance of 202. The Program Committee, under the chairmanship of Dr. H. F. Olson, had assembled a very interesting program, in spite of the difficulties of the times.

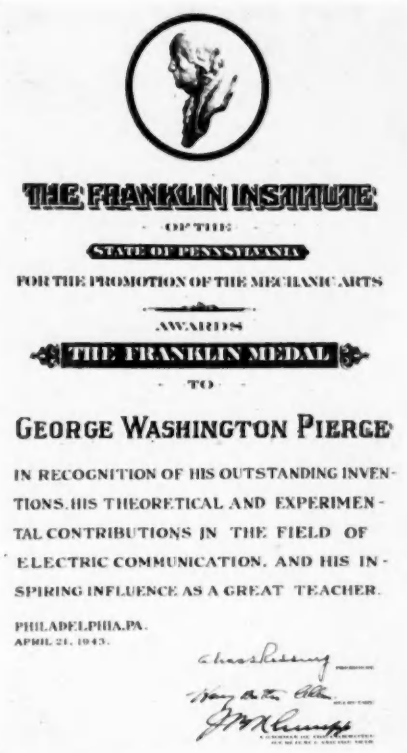
The next meeting of the Society will also be held in New York early in May, 1944. The Council realizes that New York is a considerable distance from its California members and not very close to the Chicago group, but the fact is that the center of gravity of the Society membership is not far from New York and, in order to prepare a significant program, it seems essential to hold the annual meeting in that region. There will be no meeting this Fall.

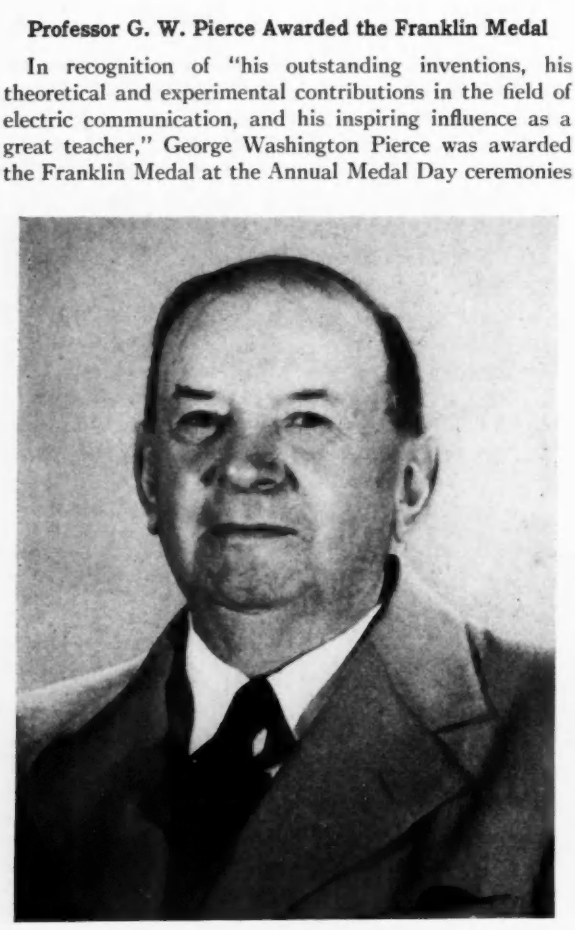
We look forward to the time when there will be two meetings a year spread about the country, the Journal will be distended with important papers, and all members of the Society will have time for leisurely contemplation of acoustical subjects.

F. A. FIRESTONE

Professor G. W. Pierce Awarded the Franklin Medal

In recognition of "his outstanding inventions, his theoretical and experimental contributions in the field of electric communication, and his inspiring influence as a great teacher," George Washington Pierce was awarded the Franklin Medal at the Annual Medal Day ceremonies


THE FRANKLIN INSTITUTE
OF THE
STATE OF PENNSYLVANIA
FOR THE PROMOTION OF THE MECHANIC ARTS
AWARDS
THE FRANKLIN MEDAL
TO
GEORGE WASHINGTON PIERCE
IN RECOGNITION OF HIS OUTSTANDING INVENTIONS, HIS THEORETICAL AND EXPERIMENTAL CONTRIBUTIONS IN THE FIELD OF ELECTRIC COMMUNICATION, AND HIS INSPIRING INFLUENCE AS A GREAT TEACHER.
PHILADELPHIA, PA.
APRIL 21, 1943.



George Washington Pierce

of the Franklin Institute in Philadelphia on Wednesday, April 21st.

Professor Pierce will be long remembered with great pleasure by all members of the Acoustical Society who were fortunate enough to be in attendance at his demonstration lecture on supersonic phenomena at the Bell Telephone Laboratories in April, 1934. In this lecture, Professor Pierce sent a beam of supersonic sound waves across the auditorium and modulated this beam to transmit music.

Professor Pierce has worked in the development of oscillator circuits for use with quartz crystals, with magnetostriction oscillators, and in the development of supersonic devices for use under water.

Reactance Slide Rule

MR. Benjamin B. Bauer has called the Editor's attention to a reactance slide rule being distributed by Shure Bros. which is just the thing for computing ωL or $1/\omega C$ or $1/2\pi(LC)^{\frac{1}{2}}$. While an ordinary slide rule will enable one to compute the above quantities, this one also keeps track of the decimal point. Obviously, it is useful for computing mechanical reactances or mechanical excitabilities, as well as electrical reactances.

Requests for these slide rules should be addressed to Shure Bros., Department 174JA, 225 West Huron Street,

Chicago, Illinois, and should contain ten cents to cover cost of handling.

Dr. H. G. Kobrak

A few days after Dr. H. G. Kobrak, of the University of Chicago, had shown his motion picture at the May, 1942 meeting in Ann Arbor, demonstrating the vibrations of the ossicles of the ear, he enlisted in the Army and has found himself so busy that his paper covering this material has been submitted just in time for this issue.

New Members

Edward P. Carter, Jr.
570 Fifth Avenue
New York, New York
Educational Department
Sonotone Corporation

John L. Carter, Jr.
Department of Physics
Brown University
Providence, Rhode Island
Instructor

Robert William Chapman
2819 Myrtle Ave., N.E.
Washington, D.C.
Radio Engineer, Broadcast Studios
Department of the Interior
Washington, D.C.

Charles William Clapp
87 East First Street
Corning, New York
Research Physicist
Corning Glass Works

Fred Bryan Daniels
194 Liberty Street
Long Branch, New Jersey
Physicist
Eatontown Signal Laboratory
Ft. Monmouth, Red Bank, New Jersey

Walter H. Eriksen
430 Bath Avenue
Long Branch, New Jersey
Associate Physicist
Signal Corps Laboratories
Eatontown, New Jersey

Sidney Thomson Fisher
1261 Shearer Street
Montreal, Quebec
Development Engineer
Northern Electric Company Ltd.

John Herbert Harding
47 Stewart Avenue
Brooklyn, New York
Engineer, Peele Company
Flushing and Stewart Avenues
Brooklyn, New York

Gregory K. Hartmann
3924 Southern Avenue, S.E.
Washington, D.C.
Associate Physicist
Bureau of Ordnance

Emil Frank Hembrooke
567 Eastern Parkway
Brooklyn, New York
Chief Engineer, Muzak Corporation
229 Fourth Avenue, New York, New York

Harry Arthur Hopf
P.O. Box 30
Ossining, New York
Management Engineer
H. A. Hopf and Company
Windrose Farm, Ossining, New York

James Raymond Lawson
Fisk University
Nashville, Tennessee
Teacher

Willard Franklin Meeker
Stromberg-Carlson Telephone Manufacturing Company
100 Carlson Road
Rochester, New York
Telephone Engineer

Albert Morrell Midgley
"Eldermere," Astons Road
Moor Park, Northwood
Middlesex, England

August B. Mundel
30 Bradley Avenue
White Plains, New York
Professional Engineer
Sonotone Corporation
Elmsford, New York

Dennis Pochmerski
426 East 14th Street
New York, New York
Inspector of Naval Material
Brooklyn, New York

George William Sherard
R.F.D. 962
Red Bank, New Jersey
Physicist, Eatontown Signal Laboratory
Eatontown, New Jersey

Einar Strommen
Dictograph Sales Corporation
95–25 149th Street
Jamaica, New York
Engineer, Acousticon Division

Ralph R. Van Atta
Owens-Corning Fiberglas Corporation
Newark, Ohio
Professional Engineer

James Edward White
532 Washington Elms
Cambridge, Massachusetts
Research Physicist
Massachusetts Institute of Technology

Donald Elwin Williamson
1302 Prescott Avenue
Ann Arbor, Michigan
Manager, Profilometer Division
Physicists Research Company
343 Main Street

Resigned: Charles H. Daines, Val R. Goldthwaite, Harold C. Mabbott, Lewis P. Reitz, Jr., E. E. Rosaire, William K. Sidwell, members; Donald MacKenzie, T. B. Munroe, Fellows.

Deceased: A. L. Kimball, Fellow; A. O. Brungardt, Ralph R. Van Atta, members.

Fellows	163
Members	703
Total membership	866

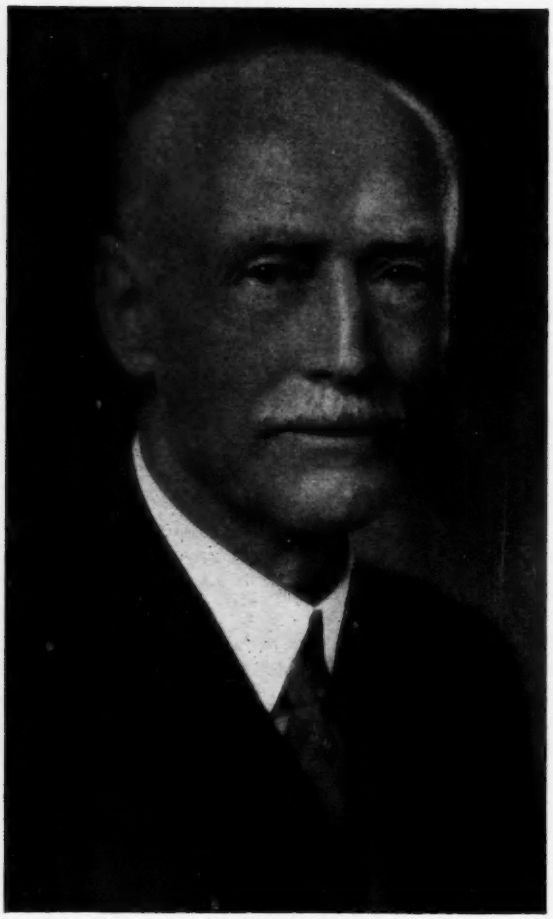
Current Publications on Acoustics

F. A. FIRESTONE
147 Randall Laboratory, University of Michigan, Ann Arbor, Michigan

Book Review

Pioneering in Psychology. CARL E. SEASHORE. Pp. 232. University of Iowa Press, Iowa City, Iowa, 1942.

Every public school teacher of music knows the Seashore "Measures of Musical Talent." The events leading to their development are but one part of this report by Dean Seashore of his forty years as director of the Psychological Laboratory at the University of Iowa. Audiometers and tonoscopes, phonetics and the teaching of speech, clinical psychology, genetic psychology, applications of psychology to education and the fine arts, all come in for their share of attention.



Carl E. Seashore

"Pioneering in Psychology" is the personal reminiscences of the man to whom people brought their problems, and whose sympathetic assistance and encouragement aided in their solution. The details of each venture are not here. They are to be found in the 231 references listed in the bibliography at the end of the volume. What is here is a review of the requirements and opportunities, and of the motives behind each development of the Iowa Laboratory as Seashore now recalls them.

A few guiding principles run through the book. Foremost is Seashore's confidence in experimental methods. Given the problem, tests and measures can be devised. The answer is found typically in a well-defined technique: the Measures of Musical Talent, the audiometric tests, phonophotography, the Meier-Seashore art judgment tests, college placement examinations. Notably absent are systematic issues. Even generalizations at the factual level are hard to find, although there are some, to be sure. For instance, Seashore strongly supports the case for a wide range in individual ability. He accepts the traditional classifications of tonal attributes, and builds his tests on them. More recently, the vibrato has emerged as the root of artistic excellence.

Cooperation among departments of the University seems almost the touchstone of Seashore's success. Reading the chapters of this book one understands the reason he was Dean of the Graduate School at Iowa for so many years. To the solution of each new set of problems the Psychological Laboratory has brought a catholicity of interest, new methods, and Seashore.

E. B. NEWMAN
Psycho-Acoustic Laboratory, Harvard University

References to Contemporary Papers on Acoustics

MOST of the titles of papers appearing in other languages than English have been translated. Abstracts in English of many foreign papers have appeared or soon will appear in Science Abstracts, Section A. Where references are made to Science Abstracts, the reference is to the volume number and abstract number. The abbreviations of the names of journals are those used in Science Abstracts and can be found in any annual index to those abstracts.

The numbers appearing at the head of each entry are the numbers which identify the subject headings in the Cumulative Index of this journal issued in November, 1939. The same Classification of Subjects can be found in the index to Volume 14.

Compiled with the generous assistance of Samuel Sass, Physics Librarian, University of Michigan.

---

2. Architectural Acoustics

2.6 **The Effect of the Mean Coefficient of Sound Absorption on the Level of Sound: Part 1.** L. D. Rosenberg. J. Tech. Phys. (U.S.S.R.) **19**, 1634–1638 (1940); Wireless Engineer **20**, Abstract 96 (1943).

4. Ear and Hearing

4.1 **How the Ear Functions (Film).** McCrory Studios (1940).

4.1 **Apparatus and Technique for Measurement of Vibratory Threshold and of Vibratory Adaptation Curve.** C. D. Aring and W. O. Frohring. J. Lab. Clin. Med. **28**, 204–207 (1942).

4.1 **Sound Perception in Beast and Man—Survey.** H. Autrum. Naturwissenschaften **30**, 69–85 (1942).

4.1 **Vibratory Sensitivity: A Quantitative Study of Its Thresholds in Nervous Disorders.** F. J. Fox, Jr., and W. W. Klemperer. Arch. Neur. and Psychiatry **48**, 622–645 (1942).

4.2 **The Acoustic Mechanism of the Cerebral Cortex.** E. Girden. Amer. J. Psychol. **55**, 518–527 (1942).

4.2 **The Significance of Micro- and Macro-Intervals between Stimulations in Investigations of Reciprocation between the Organs of Vision and Hearing.** S. N. Golburt. Ark. Biol. Nauk. **60**, 24–32 (1940).

4.2 **The Localization of Function in the Cochlea as Determined by the Recording of Electrical Potentials.** E. H. Kemp. J. Elisha Mitchell Sci. Soc. **57**, 231 (1941) Abs.

4.4 For Papers on Deafness, see Volta Review.

4.4 **Temporary Deafness in Birds.** C. W. Bray and W. R. Thurlow. Auk **59**, 379–387 (1942).

4.4 **Review of Methods Used for Estimation of Percentage Loss of Hearing.** H. A. Carter. Laryngoscope **52**, 879–890 (1942).

4.4 **Impaired Hearing in School Children.** S. J. Crowe, S. R. Guild, E. Langer, W. E. Loch, and M. H. Robbins. Laryngoscope **52**, 790–804 (1942).

4.4 **Studies in Deafness in Twins. Otosclerosis in Identical Twins. Three Case Histories.** E. P. Fowler. Laryngoscope **52**, 718–731 (1942).

4.5 **A New Telephone Set for Partially Deaf Persons.** Nature **151**, 79 (Jan. 16, 1943).

4.5 **Selecting a Hearing Aid.** Consumers Union Reports **8**, 72–77 (March, 1943).

4.5 **Hearing Aids, Boon to Mankind.** F. W. Kranz. Electronics **16**, No. 3, 111, 204–206 (March, 1943).

4.5 **Hearing-Acuity Measuring Apparatus—Audiometers.** H. Teuchert. Hoch. tech. u. elek. akus. **60**, 21–24 (1942); Wireless Engineer **20**, Abstract 88 (1943).

4.6 **A Simple Method for Testing the Hearing of Small Children.** H. Bloomer. J. Speech Disorders **7**, 311–312 (1942).

4.6 **An Improved Conditioning Technique for Determining Auditory Acuity of the Rat.** J. T. Cowles and L. A. Pennington. J. Psychol. **15**, 41–47 (1943).

4.6 **Auditory Sensitivity of the Rat.** J. Gould and C. T. Morgan. J. Comp. Psychol. **34**, 321–329 (1942).

4.6 **Testing the Acuity of Hearing.** J. H. Neil. N. Z. med. J. **40**, 222–230 (1941).

4.6 **Hello! do you hear me?** With chart showing range of hearing of common animals and range of pitch of songs of common birds. E. L. Palmer. Nature Mag. **36**, 81–88 (Feb. 1943).

4.7 **Experimental Observations on Auditory Masking.** H. G. Kobrak, J. R. Lindsay, and H. B. Perlman. Laryngoscope **52**, 870–878 (1942).

4.9 **Studies in Auditory Theory. I. Binaural Interaction and the Perception of Pitch.** J. Exper. Psychol. **32**, 17–36 (1943).

5. Applied Acoustics, Instruments and Apparatus

5.1 **Encephelaphone Converts Brain Potentials into Sounds.** Electronics **16**, No. 5, 144–148 (May, 1943).

5.4 **A New Type of Practical Distortion Meter.** J. E. Hayes. Proc. I.R.E. **31**, No. 3, 112–117 (March, 1943).

5.7 **An Apparatus for the Measurement of Fluctuations of Synchrony in Sound Carriers.** G. Guttwein. E.N.T. **19**, 85–89 (1942); Wireless Engineer **20**, Abstract 82 (1943).

5.8 **Frequency Modulation Distortion in Loud Speakers.** G. L. Beers and H. Belar. J. Soc. Mot. Pic. Eng. **40**, 207–221 (Apr. 1943); Proc. I.R.E. **31**, 132–138 (April, 1943).

5.8 **Sirens and Bells.** J. O. Perrine. Scient. Monthly **56**, 145–154 (1943).

5.9 **Bomb Scoring Made More Accurate by Microphone Method.** Sci. Am. **168**, 128–129 (March, 1943).

5.12 **An Apparatus for the Measurement of Fluctuations of Synchrony in Sound Carriers.** G. GUTTWEIN. E.N.T. **19**, 85–89 (1942); Wireless Engineer **20**, Abstract 82 (1943).

5.15 **The Noise Primer. Part III. The Decibel—What Is It?** H. H. SCOTT. General Radio Experimenter **17**, No. 1, 1–4 (Feb. 1943).

5.15 **The Noise Primer. Part IV. How to Use a Sound-Level Meter.** H. H. SCOTT. General Radio Experimenter **17**, No. 9, 4–7 (Feb. 1943).

5.15 **New Hydrodynamic Principle for Measurement of Sound. (Sensitive jets.)** H. ZICKENDRAHT. Helv. Phys. Acta **15**, 322–324 (1942); Sci. Abs. **A46**, 93 (1943).

5.16 **Glass Disks for Use in Home and Commercial Sound Recorders.** Sci. Am. **168**, 228 (May, 1943).

5.16 **Sound-On-Film; New Recorder Operates for Eleven Hours.** Sci. Am. **168**, 225–226 (May, 1943).

5.16 **Some Recent Developments in Record-Reproducing Systems.** G. L. BEERS AND C. M. SINNETT. J. Soc. Mot. Pic. Eng. **40**, 222–241 (Apr. 1943); Proc. I.R.E. **31**, 138–146 (April, 1943).

5.16 **The Variable-Density Film-Recording System Used at MGM Studios.** J. K. HILLIARD, J. Soc. Mot. Pic. Eng. **40**, 143–175 (March, 1943).

5.16 **Sound Recording Depends upon Electronics.** C. R. KEITH. Electronics **16**, No. 3, 114–115 (March, 1943).

5.19 **Tuning Forks Govern Time.** Sci. Am. **168**, 172 (April, 1943).

6. MUSICAL INSTRUMENTS AND MUSIC

6.1 **Mechanical Music of the Past.** A. H. KING. Apollo **37**, 19–20 (Jan. 1943).

6.1 **Contributions of Science to an Appreciation of Music.** A. PEPINSKY. J. Franklin Inst. **235**, 361–392 (April, 1943).

7. NOISE

7.5 **The Noise Primer. Part VI. Analysis of Noise. Part VII. How to Use the Sound Analyzer.** H. H. SCOTT. General Radio Experimenter **17**, No. 11, 1–6 (April, 1943).

7.7 **Noise Control in Motor Design.** E. HABLÜTZEL. Schweiz-Bauztg. **119**, 258–261 (May 30, 1942); Sci. Abs. **A45**, 3027 (1942).

9. SPEECH AND SINGING

9.1 **Book Review: Speech and Voice.** LEOPOLD STEIN. Nature **151**, 292 (March 13, 1943).

10. SUPERSONICS (ULTRASONICS)

10.1 **The Optics of Supersonic Waves and Supersonic Images.** O. BARBIER. Alta Frequenza **11**, 383–396 (Aug./Sept. 1942).

10.1 **Flight in the Dark: A Study of Bats.** R. GALAMBOS. Sci. Mo. **56**, 155–162 (1943).

10.3 **Focused Ultra-Sound Waves from Curved Crystals.** Sci. Am. **168**, 115 (March, 1943).

10.4 **The Measurement of the Optical ("Schlieren") Method of Supersonic Absorption in Gases.** F. A. KOROLEV. J. Exper. and Theoret. Phys. (U.S.S.R.) **11**, 184–193 (1941); Wireless Engineer **20**, Abs. 103 (1943).

10.4 **Velocity of Sound as a Bond Property.** R. T. LAGEMANN AND J. E. CORRY. J. Chem. Phys. **10**, 759 (Dec., 1942).

10.5 **Propagation of Supersonic Waves in Liquid Mixtures and Intermolecular Forces: Ether and Acetone in Chloroform—III.** R. PARSHAD. Indian J. Phys. **16**, 307–315 (Oct. 1942).

10.5 **Absorption Measurements of Supersonic Waves in Electrolytic Conducting Solutions.** W. RÜFER. Ann. Phys., Lpz. **41**, 301–312 (1942); Sci. Abs. **A45**, 3022 (1942).

10.7 **Effect of Ultrasonic Waves on the Diffraction of X-Rays by Crystals.** J. WEIGLE. Helv. Phys. Acta **15**, 329 (1942); Sci. Abs. **A46**, 90 (1943).

10.7 **Theory of the Influence of Ultrasonic Waves on the Diffraction of X-Rays by Crystals.** J. WEIGLE AND K. BLEULER. Helv. Phys. Acta **15**, 445–454 (1942). Sci. Abs. **A46**, 91 (1943).

10.9 **Supersonics in Biology.** Electronics **16**, No. 5, 154–156 (May, 1943).

10.9 **Flight in the Dark: A Study of Bats.** R. GALAMBOS. Sci. Mo. **56**, 155–162 (1943).

11. WAVES AND VIBRATIONS

11.1 **The Noise Primer. Part III. The Decibel—What Is It?** H. H. SCOTT. General Radio Experimenter **17**, No. 9, 1–4 (Feb., 1943).

11.3 **Velocity of Sound as a Bond Property.** R. T. LAGEMANN AND J. E. CORRY. J. Chem. Phys. **10**, 759 (Dec., 1942).

11.4 **On the Calculation of the Sound Field Immediately in Front of a Circular Diaphragm.** H. STENZEL. Ann. Phys., Lpz. **41**, 245–260 (1942). Sci. Abs. **A45**, 3021 (1942).

11.7 **Flutter; Detection of Vibration has Broad Implications.** Sci. Am. **168**, 220 (May, 1943).

11.7 **Free and Forced Oscillations of Continuous Beams: Treatment by the Admittance Method.** W. J. DUNCAN. Phil. Mag. **34**, 49–63 (Jan., 1943).

11.7 **The Symmetrical Vortex Street in Sound-Sensitive Plane Jets.** P. SAVIC AND J. W. MURPHY. Phil. Mag. **34**, 139–144 (Feb., 1943).

11.7 **New Hydrodynamic Principle for Measurement of Sound. (Sensitive Jets.)** H. ZICKENDRAHT. Helv. Phys. Acta **15**, 322–324 (1942); Sci. Abs. **A46**, 93 (1943).

Review of Acoustical Patents

ROBERT W. YOUNG
C. G. Conn, Ltd., Elkhart, Indiana

Printed copies of patents are furnished by the Patent Office at a cost of 10¢ each. Address all communications to: The Commissioner of Patents, Washington, D.C. Remittances should be made by postal money order, certified check, or cash. Do not send stamps.

The decimal numbers appearing before titles are the numbers which identify the subject headings in the Cumulative Index of this journal issued in November, 1939. The Patent Office classification given in parentheses with each patent entry is outlined in the "Manual of Classification of Patents" which is obtainable from the Superintendent of Documents for $1.50.

Unless otherwise indicated, patents listed have been issued by the United States Patent Office.

Reviewers

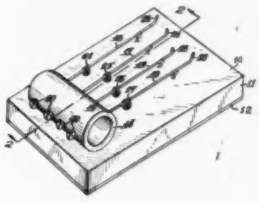
B. B. BAUER, *Shure Brothers, Chicago, Illinois*
H. A. ERF, *The H. A. Erf Acoustical Company, Cleveland, Ohio*
H. S. KNOWLES, *847 Clinton Place, River Forest, Illinois*
C. E. NELSON, *Nelson Muffler Corporation, Stoughton, Wisconsin*
L. W. SEPMEYER, *U.S.N. Radio and Sound Laboratory, San Diego, California*
R. W. YOUNG, *C. G. Conn, Ltd., Elkhart, Indiana*

2,295,902

5.7 TUNING DEVICE

Samuel M. Kass.
September 15, 1942, 3 Claims (Cl. 84–455).

"Stringed and wind instruments intended for orchestra use require tuning . . . just before a performance is to begin. This final tuning is difficult," for it "must be effected by the player who may be partially deaf." The

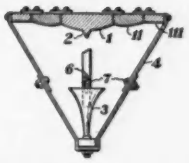


difficulty is met by a visual indicator. Sound from the instrument to be tuned acts on sounding board *10* whose vibration is transmitted through cylinder *14* to the tuned elements *28*. The motion of a rider, such as *24*, shows when tuning has been accomplished.—R.W.Y.

2,292,424

5.8 ACOUSTIC DEVICE

Alexander I. Abrahams.
August 11, 1942, 10 Claims (Cl. 181–0.5).



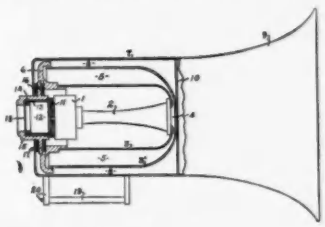
The acoustic reflector herein described is based on geometrical acoustics, and has therefore the greatest effect at high frequencies.—H.S.K.

2,301,459

5.8 ELECTRIC MEGAPHONE

Arthur J. Sanial, assignor to Guided Radio Corporation.
November 10, 1942, 3 Claims (Cl. 179–1).

The megaphone described features mechanical and acoustical insulation between loudspeaker and microphone,



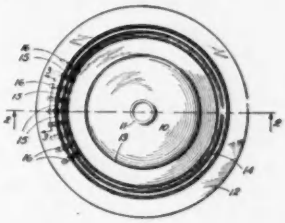
although only the 180° spatial separation of the two appears in the claims.—H.S.K.

2,302,178

5.8 ACOUSTIC DIAPHRAGM

Joseph B. Brennan.
November 17, 1942, 17 Claims (Cl. 181–32).

When a loudspeaker cone moves, the outer annular portion is usually a source of trouble because of its non-linear



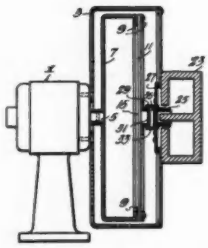
stiffness. The diaphragm described in this patent avoids this and other difficulties by introducing weak portions into the annulus.—H.S.K.

2,304,022

5.8 SOUND REPRODUCING APPARATUS

Royden C. Sanders, Jr., assignor to Radio Corporation of America.
December 1, 1942, 9 Claims (Cl. 179–108).

In the relay type loudspeaker herein disclosed the radiating surface is a rotating set of flexible blades. By various means, such as causing the hub to oscillate along



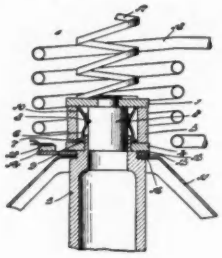
its axis, the pitch of the blades is changed from the normal zero position. No measurements are given as to frequency response, distortion, and sensitivity.—H.S.K.

2,306,291

5.8 METHOD OF ASSEMBLING THE MAGNET SYSTEM FOR ACOUSTIC DEVICES

Luitje Alons, assignor to Radio Corporation of America.
December 22, 1942, 4 Claims (Cl. 113–112).

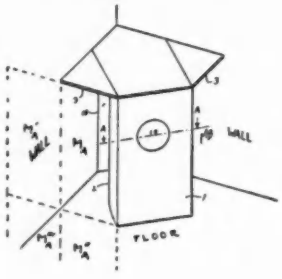
Simplified assembly of magnetic structures is claimed by tinning the parts previous to heating in a clamped condition. No mention is made of loss in efficiency to be expected.—H.S.K.



2,310,243

5.8 HORN FOR LOUDSPEAKERS

Paul W. Klipsch, assignor of twenty percent to Ray L. Smith.
February 9, 1943, 7 Claims (Cl. 181–27).



The details of this compact corner horn have been disclosed in recent issues of this journal.—H.S.K.

2,301,638

5.9 SOUND TRANSLATING APPARATUS

Harry F. Olson, assignor to Radio Corporation of America.
November 10, 1942, 6 Claims (Cl. 179–138).

Ribbon type unidirectional microphone of adjustable directivity. One side of the ribbon is open freely to the atmosphere; the other side has an enclosure, forming an acoustical delay network provided with a shunt resistance

pipe and an opening or passage defining an adjustable inertance open to the atmosphere. Directional pattern may be adjusted by varying the dimensions of the passage. —B.B.B.

2,301,744

5.9 ELECTROACOUSTICAL SIGNAL TRANSLATING APPARATUS

Harry F. Olson, assignor to Radio Corporation of America.
November 10, 1942, 32 Claims (Cl. 179–1).

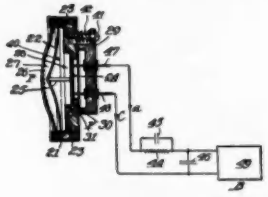
Means for obtaining an electroacoustic device of high order of directivity, by:
(a) Electrical subtraction of outputs of closely spaced pressure gradient microphones and combinations thereof.

(b) Ditto, using electrical or electroacoustic phase shifting networks in conjunction with one of the microphones.
(c) Ditto, except using electroacoustic delay and electroacoustic methods of subtraction.—B.B.B.

2,305,596

5.9 CONVERSION OF WAVE MOTION INTO ELECTRICAL ENERGY

Benjamin B. Bauer, assignor to Shure Brothers.
December 22, 1942, 14 Claims (Cl. 179–1).



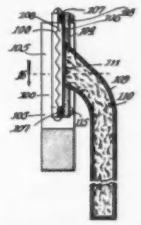
Continuation in part of Patent No. 2,237,298, describing methods for obtaining adjustable directivity patterns in a single transducer element unidirectional microphone.—B.B.B.

2,305,597

5.9 CONVERSION OF WAVE MOTION INTO ELECTRICAL ENERGY

Benjamin B. Bauer, assignor to Shure Brothers.
December 22, 1942, 15 Claims (Cl. 179–1).

Continuation in part of Patent No. 2,237,298, describing methods for obtaining a single transducer unit unidirectional microphone employing a ribbon with one side



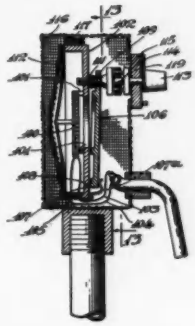
exposed to the atmosphere, and the other side enclosed by an acoustical phase-shifting network having a passage open to the atmosphere at a distance from the first side of the ribbon. Methods for adjusting directivity are described.—B.B.B.

2,305,598

5.9 CONVERSION OF WAVE MOTION INTO ELECTRICAL ENERGY

Benjamin B. Bauer, assignor to Shure Brothers.
December 22, 1942, 18 Claims (Cl. 179–1).

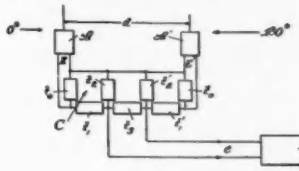
Continuation in part of Patent No. 2,237,298, describing a unidirectional microphone consisting of a single transducer with one side directly exposed to the atmosphere, and the other side provided with a phase-shifting network consisting of acoustical elements, and means for changing directivity of the microphone by altering dimensions of the acoustical elements.—B.B.B.



2,305,599

5.9 CONVERSION OF WAVE MOTION INTO ELECTRICAL ENERGY

Benjamin B. Bauer, assignor to Shure Brothers.
December 22, 1942, 23 Claims (Cl. 179–1).

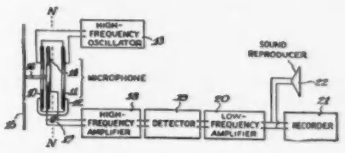


Continuation in part of Patent No. 2,237,298, showing means for obtaining a device of high order of directivity by combination of pressure gradient, and/or unidirectional microphones with electrical phase-shifting networks.—B.B.B.

2,305,626

5.9 ELECTROACOUSTIC APPARATUS

Royal Lee.
December 22, 1942, 11 Claims (Cl. 179–171.5).



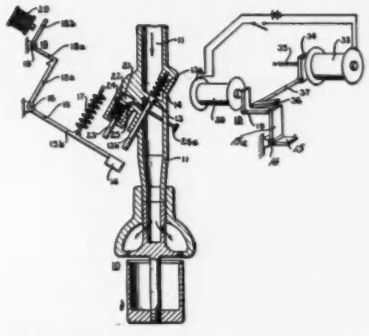
Microphone (or the like) having a local high frequency electromagnetic field set up by a pair of opposing coils *10* and *11*, and a pick-up coil (connected to the diaphragm), adapted to oscillate in the field. The pick-up coil output is in the form of an amplitude modulated carrier which is amplified and detected in the usual manner.—B.B.B.

2,294,206

5.10 SOUND TRANSMITTING MEANS FOR AIRCRAFT SONIC ALTIMETERS

Helmut Rehm and Hans Schuchmann, assignors to Siemens Apparate und Maschinen G.m.b.H.
August 25, 1942, 7 Claims (Cl. 177–8).

In the use of an aircraft sonic altimeter, a signal of very short duration is necessary when landing, in order not to obscure the echo. At higher altitudes a signal of greater duration is desired. This patent discloses simple means for making such an adjustment. Through the intermediate linkage, when coil *20* is energized, valve *13* is opened allowing the flow of fluid to whistle *10*. Then, at a rate deter-



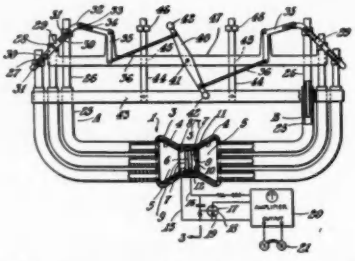
mined by the adjustment of needle valve *26a*, the fluid pressure acts on piston *22* to cock the lever *15* for the next impulse, and to allow *13* to close. In the event that coil *20* is still energized (and coil *33* in series with it), trigger *36* holds lever *15a*. Additional pneumatic means are disclosed for modifying the rate at which rod *23* is actuated, as well as more compact arrangements of the above described elements.—R.W.Y.

2,299,620

5.10 ACOUSTIC APPARATUS

G. M. Gianinni, assignor to Associated Electric Laboratories, Inc.
October 20, 1942, 4 Claims (Cl. 181–26).

A device for determining the direction of propagation of sound is disclosed which may be tuned conveniently to a single frequency or a band of frequencies by the manipulation of a single control *42*. Preliminary tuning is accomplished by closing off one side of the electrostatic



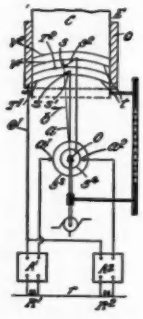
microphone *1* by the movable plate *11*, and adjusting the tubes *A* for a maximum signal. Then by the use of both sets of tubes that orientation is found for which the signal heard in the earphones is a minimum.—R.W.Y.

2,304,965

5.10 WAVE FRONT INDICATOR

Donald Orr Sproule, assignor of 1/3 to Arthur Joseph Hughes and 1/3 to Henry Hughes & Son Limited.
December 15, 1942, 5 Claims (Cl. 177–352).

Apparatus for indicating the angle of incidence of an acoustical pulse, consisting of (at least) two receivers connected to recording means which indicate the time of



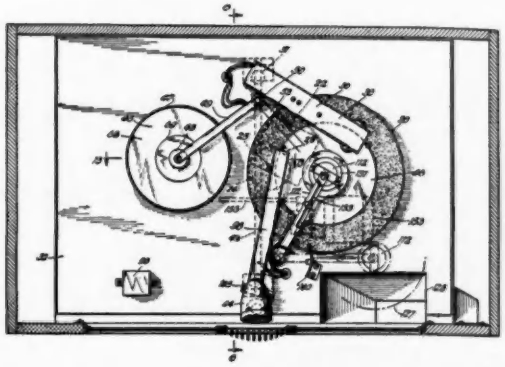
arrival of the pulse at each of the receivers; and a mechanical calculator, which is visually aligned with the recorded pulses for determination of the angle of incidence in terms of the distance between the recorded pulses.—B.B.B.

2,293,723

5.16 PHONOGRAPH

Gustav F. Erickson, assignor to James E. Johnson.
August 25, 1942, 5 Claims (Cl. 274–10).

This patent relates to a coin-operated voice recording device which essentially is comprised of a magazine of



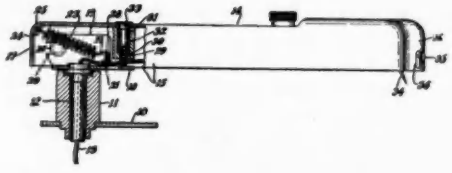
blanks having iron centers, a turntable, recording mechanism, playback, and mechanical means of transferring the blank from the magazine to the turntable and from the turntable to the delivery slot.

The normal operating cycle is recording, playback, delivery, and reloading. Electromagnets are employed in the transfer operations. Direction of recording is from outside in and the shavings are supposed to throw to the inside. At the finish of recording, as the cutter is moved outward, the shaving clinging to the stylus drags the whole coil of shavings against the surface of *112* about which the shavings are then wound, thereby clearing the stylus. A stripping device *131* later clears part *112*.—L.W.S.

2,294,575

5.16 PICK-UP ARM FOR PHONOGRAPHS

Emmor V. Schneider, assignor to Alliance Manufacturing Company.
September 1, 1942, 6 Claims (Cl. 274–1).



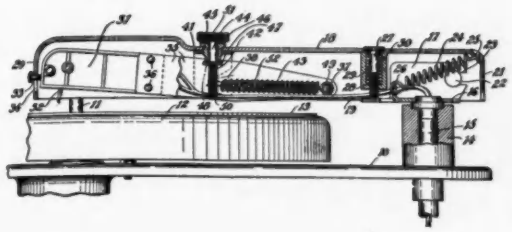
A detachable tone arm for either recording or reproducing, mounted by means of studs *22* engaging slots *20* in channeled support *19*. Spring *23* maintains arm in either operating or raised position, depending upon its position relative to studs *22*. The precise operating level is adjusted by means of screw *33*.—L.W.S.

2,294,576

5.16 RECORDING PHONOGRAPH

Emmor V. Schneider, assignor to Alliance Manufacturing Company.
September 1, 1942, 4 Claims (Cl. 274–1).

A hollow tone arm, held in position by mechanism such as disclosed in Patent No. 2,294,575, carries within it a cutter or reproducer pivoted on tangs *38* in such a manner that the needle pressure may be adjusted within fine limits.

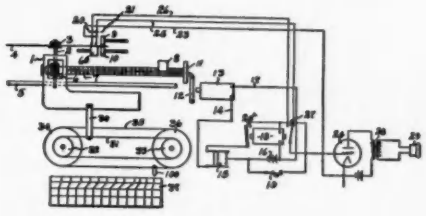


This is accomplished by moving one end *50* of the felt dampened spring *43* up or down on the screw *42*. The spring also serves to maintain the tangs in contact with the V-shaped notches formed within the surrounding tone arm.—L.W.S.

2,294,963

5.16 VARIABLE SPEED PLAYBACK FOR SOUND MACHINES

Henry Peter Clausen, assignor to The Gray Manufacturing Company.
September 8, 1942, 8 Claims (Cl. 179–100.4).

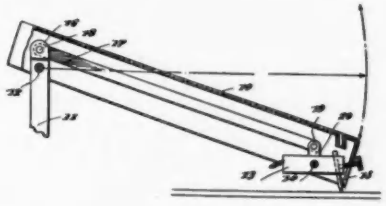


A sound machine of the constant groove speed dictating type provides an improved form of indicating device and a means of obtaining the effect of "back-spacing" and variable transcription speed by employing a multiplicity of pick-ups *20* and *21*.—L.W.S.

2,295,904

5.16 AUTOMATIC PICK-UP HEAD ADJUSTING DEVICE

Yervant H. Kurkjian.
September 15, 1942, 2 Claims (Cl. 274–1).

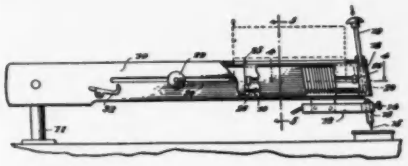


In a phonograph pick-up, a linkage *17* maintains the needle at all times at the proper angle relative to the plane of the record.—L.W.S.

2,295,905

5.16 PHONOGRAPH ARM AND NEEDLE-CARRYING MAGAZINE THEREFOR

Yervant H. Kurkjian.
September 15, 1942, 3 Claims (Cl. 274–1).

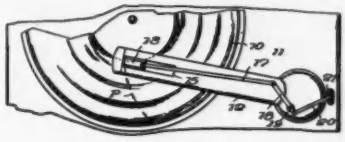


A needle magazine is included in a phonograph reproducer arm.—L.W.S.

2,303,619

5.16 ADJUSTABLE PICK-UP HEAD FOR SOUND REPRODUCING APPARATUS

Ralph B. Davis.
December 1, 1942, 4 Claims (Cl. 274–9).



This patent discloses a mechanical linkage for maintaining the axis of a phonograph reproducer tangent to the groove at all times.—L.W.S.

2,305,800

5.16 PROCESS FOR THE DUPLICATION OF SOUND RECORDING TAPES

Hugo Westerkamp, vested in the Alien Property Custodian.
December 22, 1942, 11 Claims (Cl. 18–48.5).

This patent discloses a method by which duplicates or "pressings" may be made of sound records of the tape form. This is accomplished by providing the master matrix with elevations along its edges which engage spacers whose

thickness is equal to that of the duplicate. The matrix with the spacers is wound into a spiral and the duplicates are made by either spraying or squeezing an appropriate plastic into the intervening space. Either one- or two-sided records may be made.—L.W.S.

2,309,857

5.16 RECORDING SYSTEM

Livingston Middleditch.
February 2, 1943, 5 Claims (Cl. 274–11).

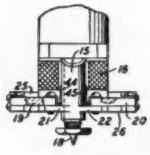
This system is a method of producing sound records of the variable density type, or a combination of variable area and variable density, by printing with ink or carbon paper upon a narrow tape of paper, celluloid, or thin metal. The record is produced by varying the pressure of the printing member in accordance with the sound impulses.—L.W.S.

2,310,048

5.16 VIBRATION TRANSLATING SYSTEM

Walter J. Albersheim, assignor to Western Electric Company, Inc.
February 2, 1943, 9 Claims (Cl. 179–100.4).

In a recording cutting head negative feedback is provided by the voltage generated in crystal elements *19* and *20* which are directly connected to the armature *15* which carries the stylus *18*. For lateral recording twister type crystals are used, benders for vertical recording. Since the voltage generated is proportional to the amplitude of motion corrective measures must be applied for constant velocity recording, but this may be done by simple electrical means.—L.W.S.



2,310,049

5.16 SOUND RECORDING AND REPRODUCING SYSTEM

Walter J. Albersheim, assignor to Western Electric Company, Inc.
February 2, 1943, 4 Claims (Cl. 274–46).

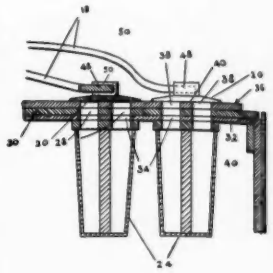
This invention relates to a method of reducing the pressure on a lateral cut record groove, particularly that caused by the "pinch effect." It is proposed that the groove sidewalls be of exponential cross section and that the reproducer have corresponding exponential shape. As shown in the figure a line contact is obtained instead of a point contact as is the case with a spherical reproducer tip riding in the bottom of a conventional V groove. How the lapidary is to produce jewels of this shape is not disclosed.—L.W.S.

2,295,156

6.1 VALVE AND VALVE SEAT FOR ACCORDIONS

George M. Bundy, assignor to H. & A. Selmer, Inc.
September 8, 1942, 2 Claims (Cl. 84–376).

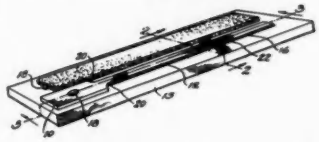
Two announced objects of this invention are to provide non-muffling faces on the movable members of accordion valves, and to simplify the replacement of the pad material when a leak develops. This is accomplished by facing the valve plate *30* with, say, a suede leather sheet and then making the valve itself of relatively hard material, possibly a plastic. The claims include mention of the recessed portion in which for final adjustment the end of the key rod *48* is held by wax *50*.—R.W.Y.



2,309,714

6.1 REED FOR MUSICAL INSTRUMENTS

Adelbert C. Radtke and Dan T. Fernandez, assignors to Sears Roebuck and Company.
February 2, 1943, 3 Claims (Cl. 84–363).



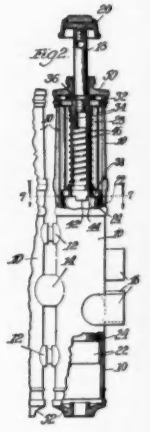
Objects of this invention are to provide a reed for an instrument such as the accordion which will not rust nor fail due to fatigue as the result of localized bending. Beryllium-copper alloy is employed, hardened, after the stamping operation if desired, by heating to 175°C for an hour, followed by air cooling. In place of the sharp corner previously used, a fillet *20* is introduced to distribute the bending over an appreciable length of the reed, thereby prolonging its life. It was found that the construction also results in a finer tone quality. Indeed "this quality is of an indescribable silvery nature, possibly due to the presence of added overtones."—R.W.Y.

2,302,914

6.3 WIND MUSICAL INSTRUMENT

Harry G. Runyon, assignor to C. G. Conn, Ltd.
November 24, 1942, 8 Claims (Cl. 84–388).

In an instrument such as a cornet, a guide of some sort is required to keep the ports in the piston properly aligned with the knuckles in the casing. This must be accomplished by a mechanism which does not impede the vertical motion and is not noisy. According to this invention the guiding action takes place at the relatively small contact rods *34*, which are carried with the piston *24* and which slide through plate *38*. The latter rests in the casing and is prevented from rotating by lug *42*. The lower portion of spring *46* fits on a tapered collar of the guide plate, thereby escaping friction with the moving stem *28*. However, the "singing" often encountered in ordinary valve springs is damped out by light contact of the remainder of the spring on the stem.—R.W.Y.

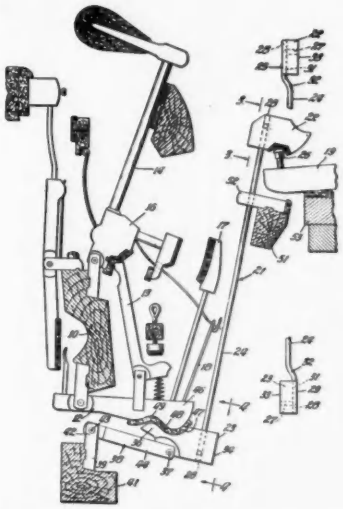


2,297,717

6.6 PIANO ACTION

Julian C. Potwin, assignor to Pratt, Read & Company.
October 6, 1942, 5 Claims (Cl. 84–240).

In this drop action for piano, although separately pivoted, the abstract *21* is carried along with the remainder of the action when it is necessary to separate the latter from the key *19*. The contact end *36* of the foot portion of the abstract is so shaped as to afford a rolling motion over felt *49*, thereby minimizing friction. To prevent the end portions *22* and *34* from moving relative to each other they are grooved along the sides and the ends of the lifter wire *24* are appropriately hooked, as shown in the two small views at the right.—R.W.Y.

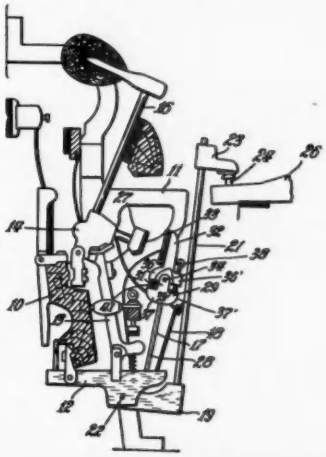


2,299,656

6.6 PIANO ACTION

Julian C. Potwin.
October 20, 1942, 10 Claims (Cl. 84–240).

Rapid repetition is dependent on the adjustment of the back check in a piano action. In a previous drop action for low pianos this adjustment was accomplished by bending the check wire *28*, but the inaccessibility of this part made the job difficult. According to the present invention the position of the back check shoe *32* is determined by the rotation of screw adjustment *38*, which can be reached easily from above. Spring *31* maintains the contact on this screw. In an alternate construction the back check may be made entirely of wood and the pivot *34* brought down adjacent to the whip *12*.—R.W.Y.

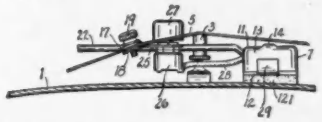


2,294,861

6.9 ELECTRICAL PICK-UP FOR STRINGED MUSICAL INSTRUMENTS

Walter L. Fuller, assignor to Gibson, Inc.
September 1, 1942, 7 Claims (Cl. 84–1.16).

This pick-up, housed in a case 7 of such a shape as to permit its use close to slanting strings, may easily be shifted lengthwise of the strings for different musical effects by releasing the clamp screw *19*. The volume control *27* is conveniently situated.—R.W.Y.

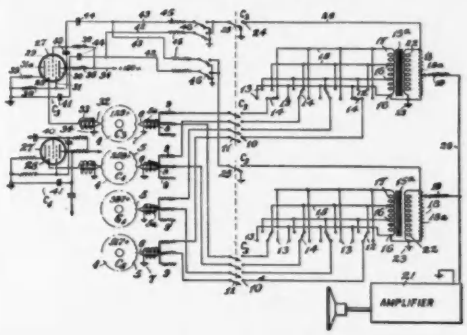


2,305,574

6.9 MUSICAL INSTRUMENT

James A. Koehl, assignor to Central Commercial Company.
December 15, 1942, 22 Claims (Cl. 84–1.19).

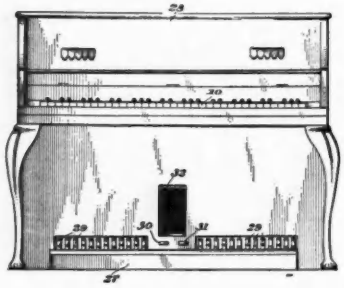
An object of this invention is to combine the outputs of two systems of oscillators in order to produce still other complex wave forms. As an example, low impedance generators *C3*, *C4*, *G4*, *C5* constitute simple sources from which a complex wave form may be synthesized. Furthermore these same generators control in some integral relation the frequencies of the corresponding vacuum tube oscillators *27*, each of which affords two wave forms through leads *42* and *43*. Through the multiple contact key switch *25* and *11* a combination of all these elements is produced in the amplifying system. A *voix celeste* may be had by controlling the oscillator *27* at frequencies differing slightly from those of the corresponding generators *C3*, *C4*.—R.W.Y.



2,305,575

6.9 MUSICAL INSTRUMENT

James A. Koehl, assignor to Central Commercial Company.
December 15, 1942, 8 Claims (Cl. 84–1.01).



This patent discloses a pedal board *29* arranged on both sides of the usual expression pedals *30* and *31*, suitable for use in a combined piano and electronic musical instrument. The swell pedal *32* may operate a suitable potentiometer. The pedal clavier, serving to control the electrical production of organ-like sounds, may be attached to an ordinary piano.—R.W.Y.

2,307,454

6.9 PIANO CONSTRUCTION

Galan W. Demuth, assignor to Radio Corporation of America.
January 5, 1943, 3 Claims (Cl. 84–188).

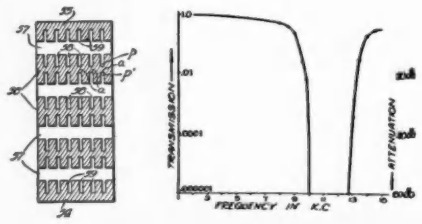
In the ordinary piano one end of the string passes over a bridge which rests on the sound board. In an electrical piano this sound board is unnecessary, so in accordance with this invention the damping of the string is reduced by supporting the bridge rigidly on the string plate. Less energy is thus imparted to adjacent strings than is the case for the usual bridge on a sound board, but air coupling suffices to retain sufficiently this characteristic of the mechanical piano. The rigid support of the string assists in keeping the piano in tune.—R.W.Y.

2,299,112

7.7 ACOUSTIC FILTER

Harold K. Schilling, assignor to Robert C. Brown, Jr.
October 20, 1942, 13 Claims (Cl. 181–48).

In the acoustic filter described, the elements are made up of acoustic reactances and do not include sound absorptive materials or acoustic "labyrinths." The shape, size, and spacing of these reactances determines cut-off frequency, attenuation, resistance to gas flow, etc. Typical applications discussed include telephone receivers and microphones, ventilating ducts, window ventilators, and transoms.—C.E.N.

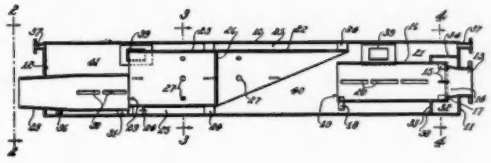


2,306,636

7.7 SILENCER

Hiram Hamilton Maxim, assignor to the Maxim Silencer Company.
December 29, 1942, 7 Claims (Cl. 181–57).

In a silencer incorporating two chambers, the annular gap between the outer casing and an inner cylinder forms the passage between the chambers. By truncating the inner



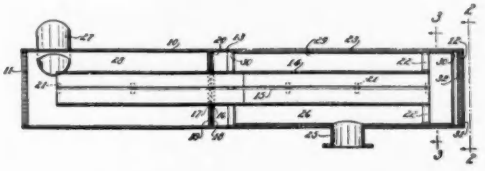
cylinder this passage is of different lengths at various points around its circumference. The description refers primarily to water-cooled mufflers such as those used on submarines.—C.E.N.

2,306,637

7.7 SILENCER

Hiram Hamilton Maxim, assignor to the Maxim Silencer Company.
December 29, 1942, 9 Claims (Cl. 181–57).

This patent describes a silencer divided into two chambers of unequal lengths. A single tube slotted or with "lateral escape openings" in the walls of the tube extends



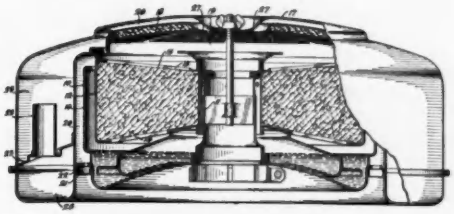
through both chambers. Simplicity of construction is stressed as is the construction in which the inlet and outlet tubes are connected to the side instead of the end of the unit.—C.E.N.

2,310,510

7.7 AIR CLEANER AND SILENCER

Benjamin Gratz Brown, assignor to General Motors Corporation.
February 9, 1943, 3 Claims (Cl. 183–15).

In an air cleaner of the "hat" type a silencer has been included so that it encircles the cleaner element, thus

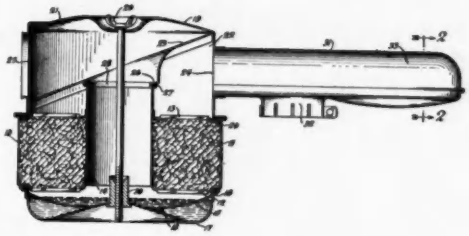


incorporating standard designs of cleaners and effecting economy in manufacture.—C.E.N.

2,310,528

7.7 AIR CLEANER

Herbert G. Kamrath, assignor to General Motors Corporation.
February 9, 1943, 1 Claim (Cl. 183–15).



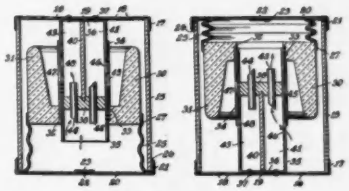
A liquid-bath air cleaner incorporating a side branch type of silencer. Claims are made for economical construction and low resistance to air flow.—C.E.N.

2,302,318

9.1 PLURAL SYLLABLE SOUND ORIGINATOR

Beulah Louise Henry.
November 17, 1942, 12 Claims (Cl. 46–187).

"The main object of this invention is to utilize the inflation period of a single bellows for the enunciation of two distinct syllables, as 'pa-pa,' and the deflation period for the enunciation of two distinct syllables as 'ma-ma,' or vice versa, upon being reversed from one upright position to an opposite position." When the device is in the position shown on the left, with the bellows *25* starting to compress under the influence of weight *30*, air has been forced through



the reed *44*, through the previously registered ports *47* and *48*, and on out through the perforations *18*. This has momentarily produced a sound as "ma," followed by silence until the reed is again excited when the rim *34* of the outer tube has passed the port *48*. A similar succession of syllables may now be produced by inverting the device (see figure on right), but this time exciting reed *42* which is reversed in direction from reed *44*. Air enters the flap valve *23* while port *46* is closed.—R.W.Y.

Program of the Twenty-Eighth Meeting of the Acoustical Society of America

HOTEL PENNSYLVANIA, NEW YORK, NEW YORK

May 14–15, 1943

1. The Vibration Characteristics of "Free-Free" Circularly Curved Bars. F. P. BUNDY, W. A. PLISKIN, AND J. E EDWARDS. (15 min.)—The positions of the nodal points and the values of the frequencies of vibration have been determined for the first five or six modes of parallel and transverse vibration of circularly curved bars of uniform cross section with central angles ranging from 356° to 60°. For vibration in the plane of curvature (parallel) the relative positions of the nodal points are the same for the same central angles, regardless of the type of cross section. Also, for the parallel vibration the frequency in the nth mode is given by the expression,

$$f_n=\frac{\theta^2K(n,\theta)}{L^2}\left(\frac{B}{m}\right)^{\frac{1}{2}}$$

where θ is the half central angle in radians, L is the length, B is the bending stiffness of the cross section about an axis perpendicular to the plane of the ring, m is the mass per unit length, and K is a "frequency constant" which depends upon n and θ. For $n>1$ or 2, K may be expressed accurately as,

$$K(n,\theta)=S^2(\theta)[n-g(\theta)]^2K(1,\theta).$$

Graphs of $S(\theta)$, $g(\theta)$, and $K(1,\theta)$ are presented. For vibrations transverse to the plane of curvature the relative positions of the nodal points depend only upon the central angle. The frequency in the nth mode of transverse vibration is given by the expression,

$$f_n=\frac{\theta^2\psi(n,\theta,A/C)}{L^2}\left(\frac{A}{m}\right)^{\frac{1}{2}}$$

where θ, L, and m are the same as defined above, A is the bending stiffness of the cross section about an axis in the radial direction, and ψ is a "frequency constant" which depends upon n, θ, and the A/C ratio. For $n>2$, ψ may be expressed quite accurately as,

$$\psi(n,\theta,A/C)=Q^2(\theta,A/C)[n-q(\theta,A/C)]^2\psi(1,\theta,A/C).$$

Graphs of $Q(\theta,A/C)$, $q(\theta,A/C)$, and $\psi(1,\theta,A/C)$ are presented.

2. The Overblowing of Organ Pipes. C. P. BONER AND R. B. NEWMAN. (15 min.)—This paper reports preliminary results of research on beating phenomena observed when organ pipes are blown at pressures substantially above normal. Various investigators have suggested that the obnoxious beating resulting from overblowing comes from inharmonic partials, vibration of pipe walls, and the like. The results of the present research indicate that during overblowing each partial of the pipe may be broken down into "component partials" of different frequencies, and that the strong beats observed are beats between members of the same "partial family." For increasing pressure the partials often occur as triplets, whereas on reduction of pressure a hysteresis-like effect occurs in which partials often appear as quintuplets.

3. Observations on the Vibrations of Piano Strings. O. H. SCHUCK AND R. W. YOUNG, *C. G. Conn, Ltd.* (15 min.)—The behavior of single struck strings in their normal positions was investigated through measurement of the frequencies and amplitudes of their partials as functions of time after striking. Three-dimensional figures showing partial amplitudes *versus* time are presented. The frequencies of the partials of the tone were found to be essentially independent of striking force and time after striking, and directly identifiable with the modal frequencies of the string. The higher modal frequencies are progressively sharp with respect to true harmonics of the fundamental; for a particular string the sharpening follows approximately a square law with respect to modal number. The resulting inharmonicity in the tone is least in the two octaves below middle *C*, rises sharply at the high end and more or less sharply at the low end, depending upon the type of piano. A correlation between inharmonicity and subjective tone quality rating is suggested, and the effect of inharmonicity upon piano tuning is discussed.

4. Criteria of Excellence in Violins. F. A. SAUNDERS, *South Hadley, Massachusetts.* (20 min.)—This report continues a series from the Harvard Laboratories of which the last was published in our Journal in January, 1941 (Watson, Cunningham, and Saunders). Recent work has produced the response curves of several excellent old and new violins, and also the rates of decay of a few of their tones. Some of these results will be shown. They disclose considerable differences in decay constants among both old and new instruments. Low damping implies greater volume of sound and an easier though slower response. Loudness (without deterioration of quality) is considered very desirable. This was demonstrated in a test conducted by two of the best violinists in this country on a large group of new instruments. The best of these were later measured by us, and showed relatively high emission in the lowest octave, and more uniformity than usual up to 4000 c.p.s. Experiments are now in progress in several places on the effects of varnish, etc., on the damping of vibrations in wood. The Chladni figures in a violin-shaped plate recently studied by J. A. Kessler (not yet published) make it clear that vibrations across the grain of the wood (whose damping is known to be very high) are as important as those across the grain. Lowering the damping of the wood by special treatment should increase the sound emission as a whole at the risk of increasing the unpleasant weakness of tones occurring between resonant peaks; but the experiment is decidedly worth trying.

5. Inhibition of Auditory Nerve Activity by Acoustic Stimulation. ROBERT GALAMBOS AND HALLOWELL DAVIS, *Department of Physiology, Harvard Medical School.* (15 min.)—For each single auditory-nerve fiber (cat) there is a "response area" clearly defined in terms of the frequency and intensity of the tones which excite activity. For most fibers the discharge of nerve impulses aroused by such adequate tones (T_1) can be reduced or abolished by other tones (T_2) or by noises (hiss or rattle) presented concurrently. Not all tones inhibit the response to T_1. Those which do inhibit fall into one or more well-defined "inhibitory areas" which are different for different fibers and for different T_1's presented to a given fiber. The inhibitory areas are adjacent to the response areas and often include some tones which lie within the response area. For a few fibers no single pure tone (T_2) inhibits the response to T_1, but in such cases the activity can usually still be abolished by noises. Inhibition of auditory-nerve activity by acoustic stimulation might result from mechanical interference in the auditory receptor or from neural interaction. Control experiments seem to exclude mechanical interference at the middle ear or basilar membrane level as an explanation. The possibility that neural interaction is involved and its implications for the interpretation of masking will be discussed.

6. Estimation of Percentage Loss of Hearing. HOWARD A. CARTER, *Council of Physical Therapy, American Medical Association, Chicago, Illinois.* (15 min.)—The Council on Physical Therapy of the American Medical Association, assisted by its Consultants on Audiometers and Hearing Aids, has formulated a method for determining the percentage loss of useful hearing for medico-legal purposes. The method has been endorsed by several leading medical societies specializing in diseases of the ear. The paper describes briefly the reasons leading up to the selection of the method and also explains how to use the audiogram charts to arrive at a percentage loss of hearing. There is a brief discussion of some of the methods that have been used prior to the formulation and adoption of the method under discussion.

7. A Reinvestigation of the Relation Between Pitch and Intensity. CLIFFORD T. MORGAN AND ROBERT GALAMBOS, *Harvard University.* (15 min.)—Pure tones were presented monaurally at octave frequencies from 125 to 8000 c.p.s. For each frequency, the pitch at different intensities was measured relative to the pitch of a standard tone of 40-db sensation level by varying the frequency until a pitch-match was obtained. Six ears (four observers) were studied. These ears differed considerably as to the direction and magnitude of change of pitch with intensity as well as to the frequencies at which the change was most prominent. With increasing intensity, the change of pitch was slight at all frequencies (maximum 3 percentage) and almost entirely absent at high frequencies (4000 and 8000 c.p.s.). The greatest changes of pitch with intensity (maximum 20 percentage) occurred in ears suffering from temporary hearing loss in part of the spectrum. These results suggest that the change of pitch with intensity is more closely related to irregularities in auditory sensitivity than to the over-all properties of the ear. This possibility may account in part for differences between these data and previous findings based upon fewer ears.

8. Acoustical Characteristics Apparent in a New Anatomy of the Human Voice. CLAIRE BENEDICT, *Chicago Musical College.* (15 min.)—This paper will set forth anatomical and acoustical confirmation of findings in the related fields of music and speech, by way of basic principles in sound causation and control as embodied in their common *instrument.* Analogies apparent in the vox humana of the pipe organ to structural and acoustical characteristics inherent in the vocal pipe will be shown: specifically, those which account for the sound effects used in or for *speech.* Further analogies in the facial structure to a three-dimensional amplifier will be supported by oscillograms in which a contact microphone was used. Final confirmation of these findings comes only from the field of application: from the response of the natural mechanics of the voice to a new technique: combining the *voicing* of this type of pipe with the blowing and fingering required in wind instruments of smaller scale; making it possible to bring the voice up to a recognized *standard* in speaking—and in all languages—as an essential preliminary to singing; and then to develop an even scale throughout the full range of the voice as used in music.

SYMPOSIUM ON MUSIC IN INDUSTRY

Chairman, HAROLD BURRIS-MEYER

9. Introduction to Music in Industry. HAROLD BURRIS-MEYER, *Stevens Institute of Technology.*—Historical résumé of music in industry: Definition of objectives. Efforts to determine the degree to which the music does its share of the work. Conflicting theories concerning the relative importance of the objectives and means for achieving them. Present state of the art.

10. Industrial Music and Morale. DAN D. HALPIN, *Victor Division, Radio Corporation of America, Camden, New Jersey.*—Internal relations can be improved by the use of the new technique of industrial broadcasting as used by numerous industrial organizations. Forty-four suggested uses are highlighted with human interest applications of these ideas. The presumptive functions of industrial broad-

casting as a technique for maintaining understanding between employer and employee, mutually represented on "Production drive committees to maintain production," will be discussed.

11. Effect of Music on Accident Reduction, EDITH HOUGH, *Safety Section, Frankford Arsenal, Pennsylvania.*—The effect of music on the reduction of accidents will be shown. This effect is in part due to lessening of fatigue and greater application on the part of the employees noticed since the introduction of music. An additional effect of the music program has been an increase in the workers' efficiency.

12. The Growing Appreciation of Music and Its Effect upon the Choice of Music in Industry. ABE PEPINSKY, *Haverford College, Haverford, Pennsylvania.*—The attempt at the reduction of boredom and fatigue among industrial workers by the use of music introduces the necessity of consideration of the individual's reaction to musical sounds. Furthermore, it should be noted that consistent exposure to musical literature tends to develop an ever-increasing appreciation of better music; better in the sense of its lasting qualities. Such a discriminatory process implies an appreciation of music supplemented, as it usually is, by the radio and phonograph in the home, together with explanatory and programmatic comment. This condition will, of necessity, demand a keen understanding of the individual's possible satisfaction or annoyance when subjected to a bath of musical sound. If such a situation is not given due consideration, we may well experience what was evidenced by a prominent restaurant in a cosmopolitan mid-western city which advertised "No Orchestral Din!"

13. Attitudes toward Types of Industrial Music. W. A. KERR, *Victor Division, Radio Corporation of America, Camden, New Jersey.*—Attitudes of four groups representing various types of occupations and backgrounds are measured and reported. Response comparisons are made and practical implications of the psychological measurements are pointed out. The procedure of scientific management of plant broadcasting is discussed.

14. Programming Music for Industry. BEN SELVIN, *Muzak Transcriptions, Inc.*—Outline of a typical day's program, suitable for industry. Discussion of types of orchestras, instrumentation and musical arrangements. Comparisons between the techniques used in the making of a phonograph record and a transcription designed for industry. Hazards of too much music. Music for luncheon periods. Discussion of the effect on industrial music of the current recording situation. The effect of employee's preferences on production.

15. The Statistical Method in Determining the Effects of Music in Industry. R. L. CARDINELL, *Stevens Institute of Technology.*—The diversity of opinion with respect to music in industry necessitates objective methods of determining the results. The primary purpose of a musical program in a plant is threefold: the relief of boredom, the relief of fatigue, and the creation of pleasanter atmosphere in which to work. Other results are secondary in nature but are, of course, of primary interest to plant management and personnel. Among these corollary results are increased production, improved attendance, reduced accident rate, fewer rejections, and better quality in the product. Plant records are not usually in convenient form to show changes brought about by music. It becomes necessary to take original data and to compute plant records to a common base. Discussion of specific examples. Particular consideration must be given to other elements which may possibly affect production. Statistical analyses are of primary importance in planning a musical program. Production rise achieved as a result of this practice far outweighs the costs involved.

---

16. Exhibition of Force at the Entrance of a Resonator. R. L. LEADBETTER, *Burgess Battery Company, Chicago, Illinois.* (15 min.)—It was about the year 1876 that Dvorak suggested an acoustic motor. He had discovered that some repelling force caused a resonator to back away from a sound source, pitched to resonator frequency. In an effort to explain this phenomenon it was necessary to assume that radiation of energy outward from the resonator opening caused a reactive force in the opposite direction. It was then necessary to assume that at any instant the absolute internal pressure on the back wall of the resonator was greater than the absolute pressure on the front wall. This really required imagination. This reactive force is easily demonstrated by attaching a number of resonators to the ends of spokes of a wheel, and mounting the hub of the wheel on a spindle. The wheel spins when placed in front of a loudspeaker generating a tone pitched to the frequency of the resonators. With the aid of titanium tetrachloride vapor it can be observed that the air flows into the opening, around the perifery, and out again in the form of a jet. On the positive half of the cycle air ejected through the entrance continues to flow outward causing air around the perifery to flow (by aspiration) toward the entrance. Obviously then, on the negative half of the resonator cycle, air flows in from the edges. In effect, this is a pulsating self-charging rocket. There is, however, a phenomenon more difficult to explain. When a light weight spherical resonator is set in a horizontal ring, smaller in diameter than the resonator, and the assembly placed in front of a loudspeaker, a tone at resonator frequency causes the sphere to roll around in the ring from any position and so orient itself that the opening is pointed directly at the most intense region of sound. This turning force is greatest when a neck-type resonator is used, as though the neck exerted a leverage on the sphere.

17. Filtered Thermal Noise—Fluctuation of Energy as a Function of Interval Length. S. O. RICE, *Bell Telephone Laboratories, New York, New York.* (15 min.)—Suppose that a source of thermal noise is connected to the input of a band pass filter. Let the output current flow through a resistance of one ohm and observe the energy dissipated in each of a number of intervals. If the intervals are of the same length T, and are taken at random, the energies have a distribution whose average and standard deviation depend upon T. This dependence is studied. Since the results are derived for thermal noise, the question of when noise may be regarded as thermal noise is also considered.

18. Conditions for Wide Angle Radiation from Conical Sound Radiators. R. W. CARLISLE, *Consultant, Elmsford, New York.* (15 min.)—The steps leading up to the general use of corrugated loudspeaker cones are briefly enumerated. The correlation between the wide-angle radiation of a hemisphere and that desired from a loudspeaker cone is considered. The mathematics of the directional pattern of a cone is developed by considering the latter to be constituted by a progression of rings of increasing size, each ring being different in phase of vibration. The directional pattern of these rings is then approximately calculated by considering a cross section through the cone as an array of pairs of point sources. This shows that wide angle radiation may be secured if there is a proper phase retardation between the center and the rim. The mathematics of a cone as an iterative network is then considered, and the conditions estimated for propagation of vibrations within a desired frequency band. The correlation between the phase retardation occurring in an iterative network and that required for wide angle radiation is demonstrated, and characteristics of experimental cones presented.

19. Recent Developments in Record Reproducing Systems. G. L. BEERS AND C. M. SINNETT, *Victor Division, Radio Corporation of America, Camden, New Jersey.* (15 min.)—Some of the more important factors in obtaining satisfactory reproduction of sound from lateral-cut phonograph records are considered. Particular reference is made to such items as vertical force of the stylus on the record, mechanical impedance of the pick-up, mechanical resonances of the pick-up and tone arm, and the over-all frequency response obtained. An experimental record reproducing system employing the principle of frequency modulation, as applied to the pick-up and its associated circuits, is described and data are supplied on the measured and calculated performance characteristics of the system. Curves are also included showing the vertical force required for satisfactory tracking with the experimental frequency modulation pick-up as compared to that required for other pick-ups of conventional design. In conclusion it is pointed out that while all the data shown apply to 78 r.p.m. records, the same performance advantages can be retained in a system designed for $33\frac{1}{3}$ r.p.m. transcription records.

20. A New Frequency Selective Vibrometer. EARLE L. KENT, *C. G. Conn, Ltd.* (15 min.)—This paper gives the theory and practice involved in the design of a small instrument which is useful in measuring the frequency, direction, and amplitude of vibration. The instrument obtains its frequency selectivity and high sensitivity by mechanical resonance. A novel method of tuning is employed which also produces variable damping in such a manner as to produce an essentially flat frequency response. The direct indicating model shown in the accompanying photographs covers an amplitude range up to 0.010″ double amplitude and a frequency range from 800 c.p.m. to 2000 c.p.m. Other ranges have been covered by other models and models have been produced using a photoelectric pick-up which made it possible to read the vibration amplitude on a meter with greater precision than on the direct indicating model.

21. An Acoustic Impedance Meter for Rapid Field Measurements. R. H. BOLT AND A. A. PETRAUSKAS, *Massachusetts Institute of Technology, Cambridge, Massachusetts.* (15 min.)—A method is developed for rapid, direct measurement of acoustic impedance. It is applicable to large panels and to materials already installed for use, and therefore offers a means of investigating effects of panel vibration and mounting conditions. The pressure and pressure gradient are measured by two microphones near the surface, in a line normal to it. If $\mathbf{p}_1$ and $\mathbf{p}_2$ are the sound pressures (time phase vectors) at the microphones; d their spacing; λ the wave-length; and θ the phase angle of the impedance; then the complex acoustic impedance ratio is given by

$$\frac{\mathbf{z}}{\rho c} \backsimeq \frac{\pi d}{\lambda}\left|\frac{\mathbf{p}_1+\mathbf{p}_2}{\mathbf{p}_1-\mathbf{p}_2}\right| e^{i(\theta-\pi/2)}.$$

This approximation is reasonably good for λ/d greater than 10 or 15, depending somewhat on the impedance value. The microphone output voltages $\mathbf{e}_1$ and $\mathbf{e}_2$ are fed into an electronic circuit which gives voltages proportional to $(\mathbf{e}_1+\mathbf{e}_2)$ and $(\mathbf{e}_1-\mathbf{e}_2)$. These combination voltages are then mixed, and adjusted in relative phase and magnitude to give a null indication. The impedance magnitude and phase angle are determined from the dial settings. Null methods are also used for calibration and alignment, which must be performed with great precision to obtain reasonably accurate results. Preliminary tests with the instrument, using commercial dynamic microphones, appear to yield satisfactory results for frequencies from 50 to 500 c.p.s. and for impedance magnitudes up to 10 ρc.

22. A Mechanical Impedance Bridge. A. M. WIGGINS, *RCA Laboratories, Princeton, New Jersey.* (15 min.)—The mechanical impedance bridge consists of two identical cantilever reeds clamped to a driving mechanism which can be driven electrically at various frequencies. Conventional condenser microphone amplifiers are used to measure the relative displacements of the reeds from their neutral positions. From the values of the relative displacements of the reeds, with one reed loaded with an unknown mechanical impedance, the value of the mechanical impedance may be calculated.

BUILDING ACOUSTICS

Chairman, VERN O. KNUDSEN

23. Steady State of Sound in a Room. H. P. KNAUSS AND J. G. WOODWARD,* *Mendenhall Laboratory of Physics, The Ohio State University, Columbus, Ohio.* (15 min.)—A relationship based on Sabine's reverberation formula and the assumption that sound from a steady source in a room reaches a uniform steady state intensity is $T=KE_0V/I_s$ where T is the reverberation time of the room, E_0 is the steady state intensity, V is the volume, I_s is the intensity within an absorbing chamber coupled to the steady source, and K is a constant. The constancy of K was tested in twelve rooms using warble tones centered at 256 and 512 c.p.s. The mean deviation of K was 33 percent at 256 and 25 percent at 512, but the value at the higher frequency was more than twice as great as that at the lower frequency. The procedure used does not yield useful values of T.

* Now at RCA Laboratories, Princeton, New Jersey.

24. The Application of Sound Absorption to Factory Noise Problems. HALE J. SABINE AND R. ALLEN WILSON, *The Celotex Corporation.* (15 min.)—This paper presents the results of experience in attacking factory noise problems by the use of sound absorbing materials. It has been borne out that the harmful effects of noise as well as the degree of relief obtainable depend not as much on the magnitudes of the noise levels as on the character of the noise. Space and time distribution of noise sources and of the resulting sound field are important factors, as are the effects of reverberation. The conventional method of calculating the reduction in average noise level due to the addition of absorption is found invalid when applied to large factory areas. Instead, results are expressed more accurately in terms of the rate of attenuation of noise level with respect to distance from the source.

25. Demountable Soundproof Rooms. W. S. GORTON, *Bell Telephone Laboratories, New York, New York.* (15 min.)—Soundproof rooms of plaster on hollow tile are effective acoustically, but have pronounced disadvantages pertaining to their construction and demolition, and have practically no salvage value. This paper describes soundproof rooms composed of panels consisting of two sheets of steel cemented to two sheets of composition board with a rockwool blanket between. The panels are of a few standard sizes, the combination of which enables rooms of almost any size to be constructed. The rooms are supported on industrial type rubber mountings for the reduction of building vibration. For the most effective attenuation of sound a second room is constructed which completely encloses the first room except that the floor of the second room consists of the floor of the building. The construction and the demounting of the rooms involve little dirt and noise, and there is practically complete salvage value. Eighteen such rooms, comprising both kinds, have been constructed in the new building of Bell Telephone Laboratories at Murray Hill, New Jersey. Single-frequency attenuation measurements have not been made owing to the pressure of war work, but noise meter measurements show an attenuation of 43 db for the single rooms and more than 57 db for the double rooms.

26. Materials and Construction for Speech Broadcasting Studios. LONSDALE GREEN, JR. (10 min.)—This paper describes the types of materials used in correcting broadcasting studios, and shows graphs of the calculated time frequency curves for studios, and also graphs showing the actual time frequency curve as determined with a high speed level recorder. This paper explains the method of testing with the high speed level recorder and also the discrepancies which occur between the calculated and actual graphs. It explains the method by which the standing waves in the room are broken up to such an extent as not to be objectionable.

27. Acoustics for Broadcasting Studios for Speech *Versus* Music. EDWARD J. CONTENT, *WOR.* (10 min.)—WOR, New York City, has recently completed three small speech studios. The factors taken into consideration are: (1) the reverberation time, (2) the shape of the reverbation time *versus* frequency curve, and (3) the reduction of the standing sound waves in the studio. This paper describes how a studio designed for good music conditions will not give the best conditions for speech; particularly speech of the news broadcast type. By lowering the reverberation at the low frequencies and allowing it to rise at the high frequencies, the effect is achieved of putting the speaker in the studio directly in the room in the home where he is being heard.

28. Acoustic Laboratory in the New RCA Laboratories. HARRY F. OLSON, *RCA Laboratories, Princeton, New Jersey.* (15 min.)—Modern facilities for development and research in all branches of acoustics are provided in the new RCA Laboratories. The new Acoustic Laboratories include the following: a free field sound room, a large sound stage, a standard living room, a soundproof room for life tests, dust-free rooms, magnetizing facilities, a live room, a field laboratory and towers, and conventional communication laboratories. The free field sound room is designed to combine acoustical conditions as obtained in free space outdoors with ideal and normal test conditions. The large sound stage is designed for tests of sound pick-up in standard conventional settings. By a change in "acoustics" the sound stage may be converted into a small theater for sound reproduction tests. The living room laboratory is designed to be the acoustical equal of the ideal living room in which sound instruments such as radios and phonographs may be developed and tested for normal home use. The soundproof

room is provided with special walls and doors for testing loudspeakers at high levels without annoyance to adjoining rooms. The dust-free rooms are used for assembling magnetic structures. The live room is designed for testing of sound absorbing materials. The conventional laboratory bays include all types of measuring equipment: oscillators, amplifiers, recorders, bridges, etc. Multiple audiofrequency lines are provided so that laboratories may be interconnected. A remotely located field laboratory is used for conducting free field response, power and life tests.

AUTHOR INDEX TO ABSTRACTS OF THE NEW YORK MEETING

Beers, G. L. and C. M. Sinnett—No. 19
Benedict, Claire—No. 8
Bolt, R. H. and A. A. Petrauskas—No. 21
Boner, C. P. and R. B. Newman—No. 2
Bundy, F. P., W. A. Pliskin, and J. E. Edwards—No. 1
Burris-Meyer, Harold—No. 9

Cardinell, R. L.—No. 15
Carlisle, R. W.—No. 18
Carter, Howard A.—No. 6
Content, Edward J.—No. 27

Davis, Hallowell—see Galambos, Robert—No. 5

Edwards, J. E.—see Bundy, F. P.—No. 1

Galambos, Robert—see Morgan, Clifford T.—No. 7
—— **and Hallowell Davis**—No. 5
Gorton, W. S.—No. 25
Green, Lonsdale, Jr.—No. 26

Hough, Edith—No. 11
Halpin, Dan D.—No. 10

Kent, Earle L.—No. 20
Kerr, W. A.—No. 13
Knauss, H. P. and J. G. Woodward—No. 23

Leadbetter, R. L.—No. 16

Morgan, Clifford T. and Robert Galambos—No. 7

Newman, R. B.—see Boner, C. P.—No. 2

Olson, Harry F.—No. 28

Pepinsky, Abe—No. 12
Petrauskas, A. A.—see Bolt, R. H.—No. 21
Pliskin, W. A.—see Bundy, F. P.—No. 1

Rice, S. O.—No. 17

Sabine, Hale J. and R. Allen Wilson—No. 24
Saunders, F. A.—No. 4
Schuck, O. H. and R. W. Young—No. 3
Selvin, Ben—No. 14
Sinnett, C. M.—see Beers, G. L.—No. 19

Wiggins, A. M.—No. 22
Wilson, R. Allen—see Sabine, Hale J.—No. 24
Woodward, J. G.—see Knauss, H. P.—No. 23

Young, R. W.—see Schuck, O. H.—No. 3